

CONSERVATION AGRICULTURE FOR SUSTAINABLE LAND USE

- The agronomic and environmental impacts of different tillage practices and plant residue retention.
- Farmer uptake of reduced tillage in England.

Kamal Alskaf (M.Sc.)

**Thesis submitted to the University of Nottingham for the degree of
Doctor of Philosophy
2018**

Abstract

Conservation Agriculture (CA) has potential benefits to the soil, crop yield, and the environment including reducing runoff, enhancing water retention and preventing soil erosion, in addition to increasing soil carbon sequestration and reducing greenhouse gas (GHG) emissions. Although CA is widely adopted in some areas of the world, it is still not widely adopted by UK farmers.

The first overall aim of this project was to investigate the effects of tillage practice and residue retention, on soil physical properties, crop yield and GHG emissions. For this purpose, a split-plot field experiment was established on the University of Nottingham farm between September 2014 and August 2016. The main plot treatment was residue retention while cultivation practices were applied to the sub-plots and included three different tillage systems: no-tillage, minimum-tillage and deep ploughing. We used a novel analytical tool, X-ray Computed Tomography, to characterise the 3-D soil pore network in conjunction with a number of other soil physical properties such as bulk density, penetration resistance and shear strength. A range of portable chambers were used to detect the GHG emissions from soil and from soil-plant systems as influenced by the tillage and residue treatments. Winter wheat yield was not affected by the tillage treatments or residue retention in the first year, but, in the second year, no-tillage caused a 10% reduction in triticale yield compared to minimum-tillage and traditional ploughing. Multiple regression analysis showed that the lower triticale yield was partially explained by higher soil strength in the no-tillage plots, together with lower soil moisture content in summer. Our results show that while there is potential for climate

change mitigation from no-tillage when the Net Ecosystem Exchange is considered, this effect could not be observed from soil emissions only.

The second aim of this project was to assess the current level of reduced tillage (RT) uptake by UK farmers and the constraints for further adoption. A postal questionnaire was conducted in January 2016. This questionnaire found that only 7.0% of the arable land in England is under no-tillage and 47.6% is under minimum-tillage. The adoption of RT increased with an increase in farm size as it was the most adopted on farms >400 ha. Moreover, RT was adopted most on combinable crop farms. Weed management and slugs were identified as main challenges for RT adopters. Increasing uptake of CA from current levels will probably require policy intervention including financial incentives for growers during the early stages of the transition from ploughing to CA. This will encourage farmers to buy RT equipment and may help them to cover any potential yield reduction, if occurred, before the CA system stabilisation.

Acknowledgements

I would like to express my great thank and appreciation to Prof. Debbie Sparkes, Prof. Paul Wilson, Prof. Sacha Mooney and Dr. Sofie Sjogersten for their excellent professional support, encouragement and friendship throughout the course of my PhD. I warmly thank them for their continued patience in shaping my professional abilities. I am honoured to be one of their students.

I would like to thank Dr Stephen Ramsden for his invaluable feedback on my presentations and annual reports. I owe gratitude to Dr Jim Craigon for his statistical advice and wisdom during the analysis of my data. I deeply thank Dr Christina Sietou for the statistical advice and STATA training. I thank Dr. Craig Sturrock and Dr. Brian Atkinson for training with X-ray CT. My gratitude is also for Michael Davies, William Spracklen, John Alcock and Matthew Tovey for helping in setting up and operating my field experiment and responding to my technical queries with lots of patience.

I am grateful to *the Aga Khan Foundation, Geneva*, for their financial support in the form of *Aga Khan Foundation-International Scholarship Programme*. Without their financial support, I would have not been able to complete this degree. This foundation continues to make positive change in this world, by enabling young people to achieve their dreams. For this noble foundation, I present my sincere respect and admiration.

I warmly thank Dr Ola Oladokun, Dr Steven Hooton and Dr Richard Gillis for their brotherhood, kindness, Friendship and advice. I will keep remembering Dr Yadgar Mahmood, Dr Ali Amamou, Dr Menaka Fernando, Dr Quan Xie, Dr Chuong Nguyen and Dr Toby Townsend for their invaluable advice during the early stages of my PhD and for being wonderful office mates.

I would like to thank my colleagues in the research group: Alistair Wright, Jake Richards, Tamara Fitters, Georgina Barratt, Annabel Hunt, Amar Alshamam, Dr. Jennifer Bussell and Dr. Agata Kaczmarek. Their invaluable feedback throughout the time of my study is highly appreciated.

I extend my gratitude to Aidan Wright, Victoria Gault, Adedeji Olutomisin Ayokunle (Tomi), Clara Goncalves Bazzo, Giovana Prado, David Boulton and Peter Carrington, for assisting in collecting gas, plant and soil samples. Their help is highly appreciated. Finally, I would like to thank farmers who participated in this study by completing the questionnaires. This work would have not been completed without their contribution.

Dedication

This achievement is dedicated to the most inspiring and generous person in my life, my father. While the Parkinson's dementia has been affected his ability to think, talk and walk, he did not leave a day without following up on my progress. I owe this achievement to my father who put the first block in my professional life by teaching me the basics of the English language since early age. Equally, this effort is dedicated to my mother, who has been observing me at all times with lots of love and affection. While she was encouraging me to work hard with optimism, she has been always giving priority to my happiness and tranquillity. Also, this endeavour is dedicated to my brother Mohamad, the great man who is standing beside me providing unlimited care and support.

Kamal

19 March 2018

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Abbreviations and acronyms

μ	Micro
μA	Micro ampere
AWCD	Average well colour development
CH₄	Methane
CO₂	Carbon dioxide
CT	Computed Tomography
g	Gram
GC	Gas chromatography
GHG	Greenhouse gas
GWP	Global warming potential
h	Hour
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
kPa	kilo Pascal
kV	Kilo volt
LSD	Least significant difference
M	Molar
mg	Milligram
min	Minute
mL	Millilitre
mM	Milli molar
N₂O	Nitrous oxide
ng	Nanogram
nm	Nanometre
NMR	Nuclear Magnetic Resonance spectroscopy
PCA	Principal component analysis
PVC	Ploy Vinyl Chloride
s	Seconds
SOC	Soil organic carbon
SOM	Soil organic matter
VG	Volume graphics
W	watt
NT	No tillage
MT	Minimum tillage
RT	Reduced tillage
PL	Ploughing

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1 Chapter 1: General introduction

1.1 Literature review

The world faces two main challenges which are food security and climate change. Conservation Agriculture (CA) is believed to be a promising tool for increasing food production while reducing the greenhouse gas emissions from agriculture. CA is a package of soil management practices which involve growing diverse crops in less disturbed soil while keeping the soil covered with organic mulch of crop residues. CA's aims are to improve soil quality, maintain crop yields and reduce soil GHG emissions ([Corsi et al., 2012](#), [Busari et al., 2015](#)). CA helps farmers increase their revenues while preserving natural resources - mainly soil and water ([García-Torres et al., 2013](#)). Based on the definition above, an optimum CA has three components (characteristics/properties) ([Kassam et al., 2016](#)):

- 1- Minimising soil disturbance through seeding directly into untilled soil or reduced tillage intensity. This helps to conserve the biological community that is expected to offer “biological tillage” in place of tillage by machinery.
- 2- Keeping the soil covered with a layer of organic matter throughout the year. This cover includes cover crops, intercrops and residues of the previous crops.
- 3- Following crop rotations that suit the local environmental conditions. These rotations should include appropriate nitrogen fixing legumes.

Over time, researchers and farmers have been applying these principles in a number of ways that suit the changing environments and different geographical areas. [Hobbs et al. \(2008\)](#) suggested adding “Controlled Traffic” to these principles to reduce the impact of

compaction. Whereas, [Vanlauwe and Giller \(2006\)](#) suggested adding fertilisation as the fourth principle where plant residues and crop yields are limited due to poor soil nutrient status such as the case in Sub Saharan Africa (SSA).

Traditionally, tillage is undertaken to provide ideal conditions for crop establishment and growth. Tillage operations can be undertaken by various types of machines that manipulate soil. Soil manipulation equipment can cut, shatter, invert or mix the soil ([Cannell, 1985](#)). The ultimate aim of tillage is to optimise productivity through improving soil physical, chemical and biological properties ([Gajri et al., 2002](#)). Large developments have occurred in the tillage equipment industry to meet various soil, climate and crop requirements. The depth of operations can be adjusted to suit soil conditions and tillage requirements as outlined in more detail below.

1.2 Tillage types in the UK

In the United Kingdom (UK), tillage takes different forms depending on the extent to which the soil is manipulated, the depth required and the equipment used. However, tillage can be divided into two broad categories (see also [Fig. 1-1](#)):

- (1) Conventional tillage (inversion tillage) refers to a number of operations that aim to prepare the seedbed through inverting the tillage layer and incorporating the previous crop residues; thereafter more operations would normally follow; such as pressing and rolling ([Carter et al., 2003a](#)).
- (2) Reduced tillage (RT) (conservation tillage, non-inversion tillage) has two main forms:

- A- Minimum tillage (MT): this system involves incorporating the plant residues with fewer tillage passes, leaving around 30% of the plant residues on the soil surface ([Davies and Finney, 2002a](#)).
- B- Direct drilling (no-till) is when the soil is left undisturbed from harvesting until sowing the following crop leaving a considerable amount of the plant residue on the soil surface. The seeds are placed in a narrow slot opened by coulters, discs or chisel ([Morris et al., 2010](#)).

In the UK, tillage systems have been developed to respond to factors such as farmers' cost pressures and timeliness of the cultivation. However, many farmers are reluctant to move away from the plough believing it is crucially important to combat weeds considering that over reliance on herbicides can cause other problems such as the development of herbicide resistant weeds so should not be used in isolation ([Heap, 2014](#)) .

1.2.1 Plough-based cultivation

Previous authors have identified the reasons that farmers use plough-based (PL) systems. Ploughing systems are believed to contribute to an improved seedbed in which drilling will be easier and crop establishment more successful ([Miller et al. 2010](#)). It helps also to bury the previous crop residues present on the soil surface, interrupt the life cycles of pests, diseases and weeds, and hence optimise the conditions for seed germination such as accelerated soil warming and drying before drilling ([Gajri et al., 2002](#), [Jordan and Leake, 2004](#)). PL systems are often undertaken by farmers when the soil structure is poor or when the soil is easily compacted, the intention being that deep

ploughing improves soil structure and increases water infiltration rate ([Morris et al., 2010](#)).

Minimum or no-tillage may leave the soil surface uneven and untidy in appearance which is important to some growers. Ploughing overcomes this issue by burying weeds and crop residues, leaving an even surface after secondary cultivation ([Jones et al., 2006b](#)).

However, there are disadvantages associated with ploughing including soil erosion, soil compaction, soil biochemical and physical degradation and the intensive workload involved ([El Titi, 2002](#)). Undoubtedly, the intensive tillage practices leave the soil bare and unprotected from heavy rain and strong wind affecting the agronomic productivity of the soil and its inherent qualities. Additionally, ploughing requires more machinery input and increases fuel consumption ([Baker et al., 2007](#), [Gay et al., 2009](#)).

1.2.2 Minimum tillage

Minimum tillage (MT) is a non-inversion tillage type. It refers to reducing the number of tillage passes and the depth of soil manipulation. Minimum tillage is typically associated with fewer passes than ploughing. The typical depth associated with minimum tillage is 5-10 cm and in this case much of the plant residues will be left on the soil surface, or 15-20 cm where more crop residues would be mixed up with the top soil ([Carter et al., 2003a](#)). Some farmers also use a “subsoiler” which is a deep non inversion tillage machine, to remove soil compaction ([Batey, 2009](#)). In practice, MT is extremely varied. For example, MT could be based on the use of tines and discs which do not invert the soil ([Christian, 1994](#)). The tine lifts and shatters the soil and removes any compacted

layers, whereas the disc follows to cut and mix the plant residues and any clods, leaving a fine tilth. Press wheels may be used to level the soil surface prior to drilling ([Morris et al., 2010](#)).

1.2.3 No-tillage (or direct drilling)

No-tillage (NT) or direct drilling is defined as placing the seeds in the soil after harvesting the previous crop with limited soil disturbance ([Carter et al., 2003a](#)). When no-tillage is applied, drilling is undertaken using a series of tines or discs that create a suitable environment for the seed. A channel in the soil is created where the seeds are placed behind the coulter, followed by a harrow or a roller to firm and level the soil. In this case, the soil will stay undisturbed from year to year and the plant residues will remain covering the soil surface. No-tillage has been observed to be successful on stable and well drained soils ([Shepherd, 2002](#)).

1.2.4 Strip tillage cultivation

The Conservation Technology Information Centre (CTIC) has defined strip tillage as a modified direct drilling system ([Fig 1-1](#)), in which less than one third of the field area is disturbed by cultivation ([Reeder, 2000](#)). The seeds are drilled in the strips in autumn or spring. Plant residues are relocated to the area between the strips. Within UK arable cropping fields, strip tillage has potential benefits over ploughing, as it includes enhancing soil biodiversity and improving soil physical properties ([Reeder, 2000](#)). In strip tillage system, residue retention conserves soil water through reduced evaporation, protects soil from erosion and preserves the soil environment suitable for wildlife ([Licht and Al-Kaisi, 2005](#)). In the US, strip tillage is widely used as an alternative to other

reduced tillage forms. In autumn or spring, strip tillage takes place by creating a fine tilled strip of 10-20 cm wide. This leaves 60-75% of plant residues undisturbed on the soil surface between the strips, which will reduce soil moisture evaporation and increase temperature (Al-Kaisi and Hanna, 2002). As the spaces between the strips can be any width, strip tillage is suitable for both cereals and root crops (Bolton and Booster, 1981, Nuttall and Stevens, 1982, Spieser, 1984, Eash et al., 2002, Lee et al., 2003, Luna and Staben, 2003, Khalilian *et al.*, 2004). The soil disturbance caused by this method depends on the design of the tine and disc combination being used to create the strips. Thus, some designs create more disturbance than others (Overstreet, 2009). For instance, at a given depth, greater soil disturbance is created by using a winged tine rather than a knife tine (Morris et al., 2007).

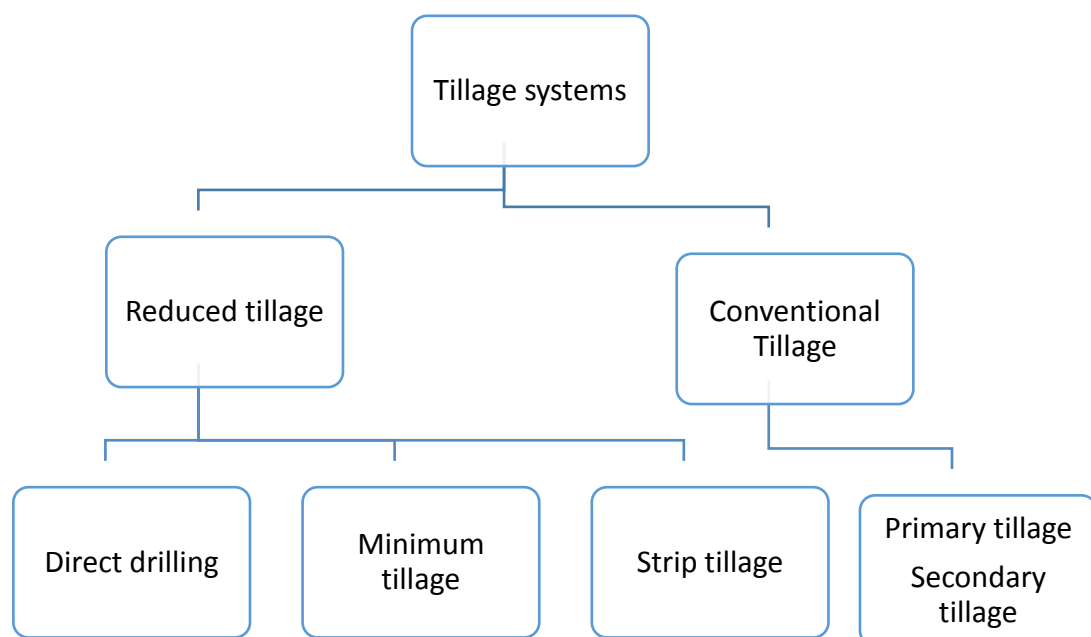


Fig. 1-1. Classification of tillage systems in relation to tillage intensity (Morris et al., 2010).

In the remainder of this chapter, the term reduced tillage is used to refer to all soil tillage and crop establishment techniques that do not include inverting the soil surface (i.e.

non-plough-based systems). Therefore, reduced tillage includes shallow minimum tillage, deep minimum tillage, strip tillage and direct drilling. The reduced tillage focus within this thesis largely relates to no-tillage and minimum-tillage.

1.3 The importance of reduced tillage

One of the crucial factors with respect to choice of tillage practice in the UK is the timeliness of crop establishment. The importance of timeliness was not well acknowledged in the 1970s, which has been hypothesised to be one of the reasons that reduced tillage was not widely adopted at this time (Carter et al., 2003a). Under the temperate weather conditions in Northern Europe, for winter crop establishment, farmers have a narrow time window after harvesting one crop to establish the following. The time gap varies depending on the previous crop and the following crop, and the time needed for seedbed preparations (Morris et al., 2010). Reduced tillage reduces cultivation time requirements in comparison to plough based systems, allowing a larger area of the land to be sown within the optimum time window, before the onset of late autumn and winter. This reduces time pressure on labour and machinery needs (Cannell, 1985, Ball, 1987). Less inputs (fuel, labour, machinery) are therefore required during reduced tillage in comparison to plough-based systems.

In general, reduced tillage forms have many benefits on soil retention (reducing erosion), moisture content, organic matter, and soil physical and chemical properties that can have a positive effect on reducing greenhouse gas (GHG) emissions from the soil, and hence reduce the impact of agriculture on climate change. Theoretically, all these benefits should encourage farmers to adopt reduced tillage, specifically

minimum-tillage and no-tillage in particular (Cannell, 1985), but in reality, adoption in some countries is either slow or non-existent (Farooq and Siddique, 2015).

Reviewing the literature on this topic demonstrates that the adoption of reduced tillage practices varies according to many factors ranging from soil type, machinery availability and climate conditions. Soil erosion is a main driver for the adoption of the reduced tillage practices in some areas - in particular in South and North America with a noticeable increase in Africa, Australia and other arid and semi-arid areas (Holland, 2004). In other areas, less prone to soil erosion, cost saving is more likely to be the main driver for the adoption of reduced tillage (Morris et al., 2010). This is typically the case in Europe and other temperate areas. Cost saving includes lower consumption of fuel and lower labour inputs, which can result in increased profits if yield is maintained or even slightly reduced (Bailey, 2007).

1.4 The interaction between soil and crop

The interaction between plant and soil is complex. Understanding soil quality and its behaviour following different agricultural practices are essential for maintaining soil and crop production. Soil quality has the vital role in sustaining biological productivity and promoting plant growth (Doran and Parkin, 1994). Therefore, soil quality assessment influences food security and economic issues as well as the environmental importance (Larson and Pierce, 1994, Lal, 1999, Herrick, 2000). Soil has inherent and dynamic properties which are considered in any assessment process (Karlen et al., 2003). Soil properties and quality are affected by several factors such as cropping history (previous crops), climatic conditions, tillage system and organic matter addition/supply in the current and previous years (Mahboubi et al., 1993, Chagas et al., 1995).

During the last decades, the popularity of Conservation Agriculture practices has increased due to their positive impacts on soil properties ([Grant and Lafond, 1993](#), [Dao, 1993](#)). However, other studies have found negative effects of Conservation Agriculture on some of these soil characteristics as a result of the reduced tillage. For instance, reduced tillage could lead to increased soil compaction which can be defined as: “the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density” ([Soil Science Society of America, 1996](#)). Soil compaction is influenced by few factors such as soil moisture content ([Lipiec et al., 2002](#), [Soane and van Ouwerkerk, 2013](#)) and machine traffic ([Horn, 2003](#)). Several studies have shown that soil physical and biological factors are responsible for the reduction in cereal crop yields ([Hammel, 1989](#), [Mahboubi et al., 1993](#)) with higher risk of losing yield under no-tillage ([Cornish and Lymbery, 1987](#), [Kirkegaard et al., 1994](#)). A study by [Benito et al. \(1999\)](#) (reviewed in [Hamza and Anderson \(2005\)](#)) compared the effects of traditional ploughing, minimum tillage, and no-tillage on soil moisture content, soil organic matter and soil compaction. The findings of this study were that soil moisture was greatest in no-tillage than the other treatments and soil organic matter was greater in no-tillage and minimum tillage than ploughing in the upper soil surface. They found also that ploughing caused highest soil compaction in the subsoil, but the soil compaction was highest in the no-tillage in the upper soil surface. The effect of the compaction means two things: a) the branching and spread of the roots would be mechanically impeded and b) water logging which could lead to poor aeration, which is necessary for roots and soil microbes to flourish. Mechanical restriction would limit the movement of water and minerals and make them less available for the plants ([Oussible et al., 1992](#)). To understand this complex relationship

between soil and crop management, some of the effects of both of reduced tillage and residue retention on soil quality are explained below.

1.4.1 The effects of soil tillage on soil quality

1.4.1.1 Tillage effects on seedbed quality and aggregate stability

The main role of tillage is to create an optimal seedbed for seed germination and crop establishment (Gajri et al., 2002). Seedbed quality is determined by aggregate size distribution which has a great influence on crop emergence (Morris et al., 2010). Tillage is expected to create a layer below the seeds which is consolidated to ensure the movement of the soil water upwards and a thin layer of soil above the seeds, that consists of fine aggregates ensuring optimal soil-seed contact (El Titi, 2002). Different tillage practices affect seedbed quality according to the soil type. However, in all soil types, reduced tillage increase the organic matter over time creating a better seedbed (Wade et al., 2006) and improving soil structure and the functionality of soil properties (Davies, 1993).

Cultivation systems influence the soil aggregate distribution and therefore have a great influence on seedbed quality. However, any particular cultivation system determines the seedbed quality based on the soil type and soil conditions such as moisture and temperature (Wade et al., 2006). Reduced tillage forms increase soil organic matter creating higher aggregate stability compared to ploughing (Marshall and Holmes, 1988). However, impairment in crop establishment has been reported because of the large aggregates which reduce the seed-soil contact and cause variation in the seeding depth (El Titi, 2002). In Australia, Zhang et al. (2007) conducted a 25 year study to compare the effects of no-tillage (stubble retained) and ploughing (stubble removed) on

aggregate size in the upper 5 cm of the soil surface. This study showed that no-tillage increased the macro-aggregates (>2 mm) compared to ploughing (165 g kg⁻¹ and 78 g kg⁻¹ respectively). This result was attributed to the role of organic matter in combining soil particles increasing the aggregate sizes. Furthermore, reduced tillage forms increase soil aggregate resistance to water runoff and make the untilled soil water repellent (El Titi, 2002). In contrast, soil aggregates in ploughed soils are fragile and they get wet rapidly, consequently these soils are susceptible to structural damage during rain-storms (Marshall and Holmes, 1988).

1.4.1.2 Tillage effects on soil strength, soil boundaries and soil compaction

There is a relationship between tillage system, soil strength and root penetration. Soil strength is the result of the cohesive forces between soil particles and their resistance when they are forced to slide over one another (Marshall and Holmes, 1988). Ball and O'Sullivan (1982) found that reduced tillage, especially no-tillage increases soil strength. This affects the plant emergence rate as the root growth would be mechanically hindered (Pietola, 2005). Under no-tillage, it was found that wheat root growth was impeded when soil strength was more than 1.5 MPa and the seminal roots were restrained when 1.4 MPa in the upper soil layer (Schjønning and Rasmussen, 2000, Schjønning and Thomsen, 2006). Increasing soil moisture content decreases soil strength due to the role of absorbed water in weakening the bonds linking the structural units (Marshall and Holmes, 1988).

In many cases, ploughing is undertaken to reduce soil strength, but high strength soil may also be found in ploughed soils (Pietola, 2005). A “plough pan” can be formed when ploughing is undertaken regularly to the same depth in wet conditions (Davies, 1993).

A remedial action for compaction is the rational utilisation of a subsoiler (Davies and Finney, 2002a). However, the benefits of a subsoiler in alleviation soil compaction is limited (Batey, 2009). Using subsoiler to remove compaction from the deep soil layers may use more fuel than deep ploughing (Morris et al 2010). The strength of the upper soil surface, located above the compacted layers is a limiting factor for using the subsoiler. This layer should be sufficiently fragile to allow the tines of the subsoiler to shatter the compacted layer. Having high soil moisture content may make the usage of the subsoiler easier.

Soil compaction may deteriorate root shapes reducing the growth of the plants (Whalley et al., 2005). When the soil is compacted, plant roots were shorter and less able to penetrate deeper layers. The roots became buckled which means that they had larger diameters and increased lateral roots in looser soil zones (Pietola, 2005). Plant growth is associated with the roots' ability to elongate and reach areas of water and nutrients (Clark et al., 2003).

1.4.1.3 Tillage effects on soil temperature and moisture

Soil temperature and moisture content are affected by tillage. Under reduced tillage, the likelihood of moisture and temperature conservation is higher than ploughing. Reduced tillage practices decrease evaporation through which water and heat are lost naturally. Soil disturbance increases the air pockets within which evaporation takes place (Licht and Al-Kaisi, 2005). Soil disturbance also changes soil flora and fauna structure which has an important role in soil moisture content and soil temperature (Marshall and Holmes, 1988).

Among the different types of reduced tillage, no-tillage is the most efficient form in moisture and temperature conservation as the soil surface exposed to the external weather factors is the lowest (Al-Kaisi and Hanna, 2002). Soil temperature and moisture are interlinked. Dry soil can be affected by temperature change more than wet soil, due to the fact that water has a higher heat capacity and lower heat conductivity than soil particles; therefore, wet soils warm and cool slower than dry soils (Davies, 1993). As reduced tillage is more likely to increase the soil moisture content, it slows down the soil temperature change.

1.4.2 Crop residue management

1.4.2.1 The effects of crop residue on soil temperature and moisture content

Plant residue retention is one of the factors which controls soil temperature (Beyaert et al., 2002). This effect is demonstrated in a number of ways. A) Plant residues form an insulating layer protecting the soil surface from the above ground conditions; consequently, this layer limits the temperature exchange between the air and soil. B) Plant residue layer is better at reflecting solar radiation than bare soil, so this layer reduces the soil evaporation rate causing a slow warming up of the soil (Shinners et al., 1994). These effects seem to be in favour of plant growth, but it may have negative effects as well. For example, Børresen and Njøs (1990) reported that the retention of 4 tonnes per hectare of plant residues, reduced the soil temperature by 2.5 degrees at a depth of 2 cm. This affected maize emergence by leading to a loss in yield by 4 t.h⁻¹. It might be that the plants needed higher temperature during the growth season in spring and summer to guarantee the growth of the roots. Another expected reason could be

the effects of low temperature on soil's flora and fauna which play an important role in improving the soil structure and root expansion.

Plant residue retention also increases soil moisture content. [Beyaert et al. \(2002\)](#) stated that having more than 70 % of the field soil surface covered with plant residues increased moisture conservation during high water demand. As the ploughing decreases the soil moisture content compared to no-tillage, it was found that plant residue retention reduces this difference ([Azooz et al., 1997](#)).

1.4.2.2 The effects of crop residue on soil (organic matter, erosion, crust, infiltration)

Plant residue retention has a crucial impact on soil. It protects the soil from wind and water erosion ([Boatman et al., 1999](#)). In the UK alone, this soil loss is estimated at 2.3 million tonnes of soil per year ([Carter et al., 2003b](#)) through which large amounts of nutrients and pesticides are lost leading to pollution of water resources through eutrophication and sedimentation. Reduced tillage practices reduce soil erosion and consequently, nutrient loss due to reduced runoff ([Carter et al., 2003b](#)). This might be due to the plant residue retained on the soil surface. [Shinners et al. \(1994\)](#) found that when plant residues covered only 20% of the soil surface, soil erosion was reduced by 50%. Among the forms of the reduced tillage, no-tillage looks the most effective as it led 426 kg ha⁻¹ soil loss compared to 9050 kg ha⁻¹ after ploughing ([Blevins and Frye, 1993](#)). This was due to the plant residues left as stubble reducing raindrop impact, so soil aggregates are not broken up ([Fawcett and Caruana, 2001](#), [Morrison and Sanabria, 2002](#)). By comparing the impacts of ploughing, minimum-tillage and no-tillage on soil by [Tebrügge and Düring \(1999\)](#), they found that the applications of minimum-tillage were intermediated between ploughing and no-tillage.

In high rainfall areas, plant residue retention is important to prevent the formation of a soil crust. In these weather conditions, raindrops break down small soil aggregates leading to their displacement. Then soil particles relocate in a continuous structure creating a surface seal or surface crust when it dries (Awadhwai and Thierstein, 1985, Ramos et al., 2003). Surface crust reduces soil infiltration rate and increases soil erosion (Awadhwai and Thierstein, 1985, Franzluebbers, 2002, Ramos et al., 2003). Soil crust formation accelerates when the silt proportion is high in the soil (Ramos et al., 2003) and impedes crop establishment (Awadhwai and Thierstein, 1985). Plant residue retention may dissipate the energy of the raindrops before they hit the soil surface reducing the formation of a soil crust (Fig. 1-2).

Plant residue retention increases soil organic matter. Over time, micro-organisms break down plant residues into organic matter which combines soil particles forming stable aggregates, and consequently improves the soil structure (Fawcett and Caruana, 2001). Soil organic matter increases soil porosity, maintaining the aerobic conditions which are required for plant root growth (Boatman et al., 1999). Therefore, plant residues are important for improving the soil structure.

Plant residue retention improves soil infiltration rates (Franzluebbers, 2002). In a study which lasted for 25 years, Franzluebbers (2002) found that, while the infiltration rate was only 28 cm h⁻¹ in ploughed soil, it was 72 cm h⁻¹ in non-tilled soil. Improved infiltration rate was attributed to the plant residues retained on the soil surface under no-tillage (Ashman and Puri, 2013). Plant residues extended the pore network from the surface horizons to the subsoil, ploughing damages this network of channelled, tubed-shaped and elongated pores. When the soil is ploughed, the infiltration rate increases

initially as opening the soil with ploughing machines allows the movement of the water and air. After a short period of time, the infiltration rate decreases because of the sealing of the soil pores due to the lack of plant residues on the soil surface (Marshall and Holmes, 1988, Blevins and Frye, 1993).

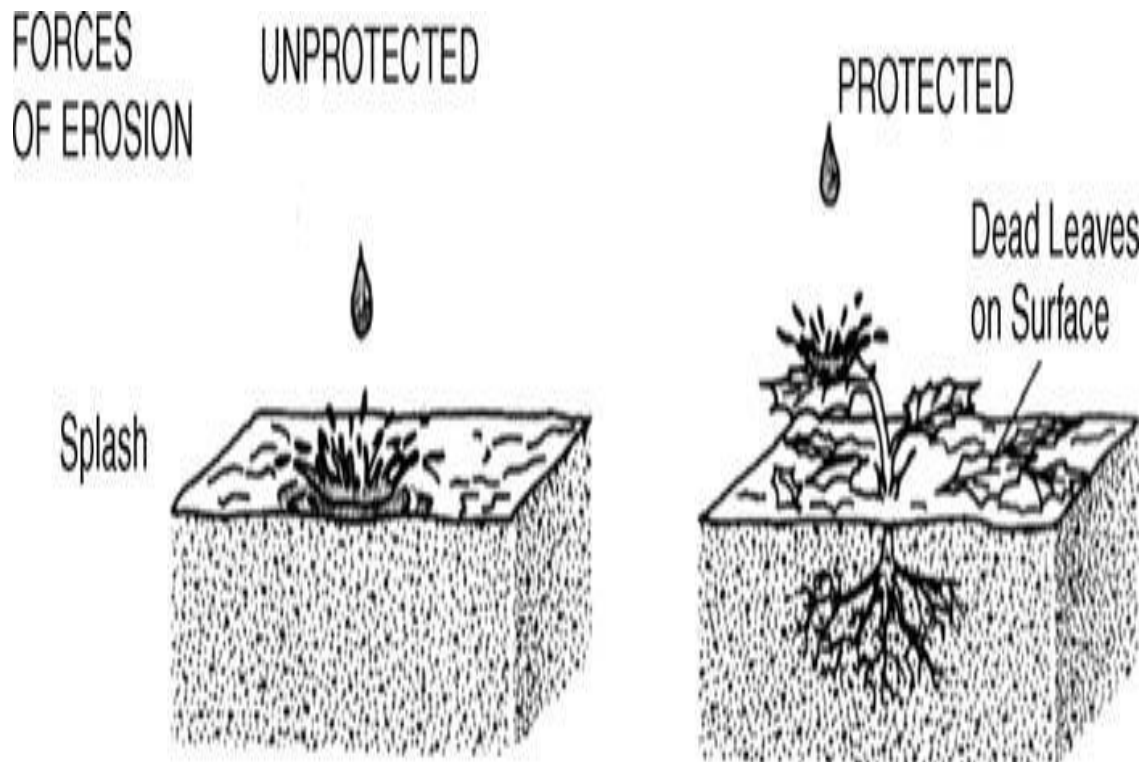


Fig. 1-2. The effect of crop residue on the dissipation of raindrop impact energy (Redmon, 2002).

1.4.2.3 Implements to deal with crop residues (Concerns about plant residue retention)

For satisfactory crop growth with reduced tillage, residue management has a crucial role. Incorporating plant residues in the soil surface brings several benefits to the soil (Sprague and Triplett, 1986). However, plant residues may have a negative effect on plant growth and yield. Harper (1989) found that leaving the residue on the soil surface could lead to 50% reduction in the plant population due to the formation of large soil clods and thick clumps of stubble which impeded seedling emergence. Thus, Al-Kaisi and Hanna (2002) recommended reducing the amount of the plant residues incorporated.

The negative effects of crop residue retention could take place in many ways. First, residue retention may reduce the soil-seed contact reducing seed emergence. The soil-seed contact is an important factor for successful emergence. If the seeds are planted in the crop residues only, then there will be no contact between soil aggregates and seeds. Consequently, the emergence will be poor (Sprague and Triplett, 1986). Also, when the residues are present in the soil, sealing of the seed slot may not be effective happen and then soil and rain will drain into this space. This is more likely to cause anaerobic conditions which hinder seedling development (Harper, 1989). Second, blockages in the drill are one of these concerns. This problem depends on the length of the residues. If the straw is longer than 7.5 cm, it blocks the drill, but if the straw is shorter, it does not cause problems for drill as its implement pushes the straw aside (Baker et al., 1996). The residues are more likely to cause blockages if they are left/positioned in narrow rows near to the seeds. In this case, residues would gather in clumps covering the seeds spaces and this would reduce the seed emergence (Siemens et al., 2004). If the coulters become blocked, soil from one row to another will be thrown creating uneven soil surface (Siemens et al., 2004). There are many recommendations to overcome this problem. 1) A space of 25 – 45 cm between rows is recommended as this would improve residue clearance between coulters (Allen, 1988). 2) using disc coulters which cut through the residue without being blocked with residues (Morris et al., 2010). 3) Using a wheel to clear the residue from between the rows. This method led to a 14 – 17 % increase in the establishment (Siemens et al., 2004) as it could lead to a up to 70% reduction in the plant residues from between the planting rows (Raoufat and Matbooei, 2007). Third, crop residues may release water-soluble toxins (such as phenolic acids or acetic acid) which could have detrimental effects on crop

establishment. These phytotoxins are produced by crop residues or micro-organisms under anaerobic conditions during the residue decomposition process (Kimber, 1967, Hamblin et al., 1987, Harper, 1989, Alam, 1990). It is believed that shallow tillage incorporates residues into the soil surface and produce minimal disturbance to the soil preventing the anaerobic conditions and, consequently, the formation of the phytotoxins. The symptoms of the phytotoxins on plants could be observed in many ways such as yellow leaves, reduced tillering and spindly stems, which are all factors that decrease crop yield. Furthermore, decomposition of wheat straw produced phytotoxins which hinder germination, and limit root and shoot growth (Elliott et al., 1978). Lovett and Jessop (1982) found that the retention of wheat residues led to 60 % reduction in the emergence of the plant and to 10% reduction in the coleoptile height compared to the controlled areas. This reduction was attributed to the phytotoxicity of the plant residues (Elliott et al., 1978, Wuest et al., 2000). The toxicity effects are determined by the time between the plant residue incorporation and the sowing date and the residues position compared to the seeds. It is believed that the shorter the time, the greater inhibition impact would be (Kimber, 1967, Elliott et al., 1978, Roth et al., 2000).

1.4.3 The challenges for reduced tillage and residue retention

Reduced tillage forms are often restricted by the increase in weed population. From weed management perspective, inverting soil surface through ploughing is an effective way to bury the weed seeds to a depth below which they cannot grow (Froud-Williams et al., 1983a, Froud-Williams et al., 1983b, Froud-Williams et al., 1984). Relying entirely on herbicides does not seem efficient as weed resistance may increase over time and

there is an increasing pressure to reduce the usage of the herbicides for environmental concerns, high cost, thus these reasons might have made reduced tillage less popular by some farmers (Moss et al., 2007). However, under the UK conditions, Bullock (2004) found that and using stale seedbeds minimised the weed burden. Orson (1996) reported that drilling after the 20th of October in high dormancy years reduced the population of *Alopecurus myosuroides*, but this may cause reduction in the yield if the crop establishment was poor and followed by a dry summer. Different weed species respond differently to minimum tillage. For example, minimal soil disturbance stimulates the germination of *Anisantha sterilis* (Edwards, 2006). As the weed seeds are not buried in the soil surface under reduced tillage, Chauhan et al. (2012) found that this reduce a positive effects on weed management due to seed desiccation and predation by insects. When reduced tillage is undertaken, the amount of the surface residues increases, this is usually associated with increase of pests such as slugs. Slug control is one of the main concerns for reduced tillage adopters (Davies and Finney, 2002a). Farmers tend to deal with this pest by using slug pellets. This issue might be more serious with no-tillage as the amount of stubble left on the soil surface is larger than in minimum-tillage. Furthermore, the incidents of the diseases such as *Rhododendron. Herpotrichoides* (eyespot) and *Septoria. Tritici* (leaf spot) increased when reduced tillage was undertaken and plant residue retained allowing carry over of disease between crops.

1.4.4 Soil structure and porosity

Soil structure determines the soil conditions such as moisture and air which govern the actions of soil microbes and the decomposition of the organic matter (Strong et al., 2004). Soil organic matter and pore network are inseparable entities and they change

continuously over time. Initially, reduced tillage may decrease total soil porosity in the upper part of the soil surface (Kay and VandenBygaart, 2002) due to reducing the volume of the macro-pores compared to ploughed soil (Schjønning and Rasmussen, 2000). However, gradually, the adoption of reduced tillage will increase the number of macro-pores especially in the upper part of the soil surface due to the organic matter accumulated in this depth enhancing the biological activities (Bronick and Lal, 2005, Zhang et al., 2007). Moreover, Kay and VandenBygaart (2002) found that macro-pores increased in size as a result of the soil organisms enhanced by the abundance of the plant roots and plant residues. Arshad et al. (1999) noted that micro-pores exist in high numbers under no-tillage and plant residue retention. Micro-pores and surrounding soil aggregates have the possibility to protect soil organic matter from decomposition (Bachmann et al., 2008).

1.4.4.1 X-ray Computed Tomography- Advanced techniques to measure soil pore characteristics

The principle of the Computed Tomography (CT) is the attenuation of an electromagnetic beam from an object of interest. The X-ray beam is attenuated when it passes the sample, this attenuation is recorded by a detector (Heeraman et al., 1997) (Fig. 1-3). Equation 1 shows Beer's law which describes the attenuation of homogeneous samples.

$$I/I_0 = \exp(-\mu h) \quad \text{(Equation 1)}$$

μ : the linear attenuation coefficient (L⁻¹)

I_0 : the intensity of incident X-ray beam

I : the intensity of incident attenuated X-ray beam

h : the sample thickness.

CT scanning produces images representing the linear attenuation coefficient of an object depending on the density of the materials of the scanned object. As Beer's law does not provide accurate results for heterogeneous soil samples, it has been modified by different scientists to demonstrate heterogeneous materials such as the soil components by calculating the path length within each soil sample (Ferraz and Mansell, 1979).

Following the work of Petrovic et al. (1982) on soil bulk density, the use of X-ray CT has been extended to investigate a range of soil physical properties. This technique has provided a good explanation for the effects of the different tillage practices on soil structure (Pires et al., 2002, Taina et al., 2008, Papadopoulos et al., 2009).

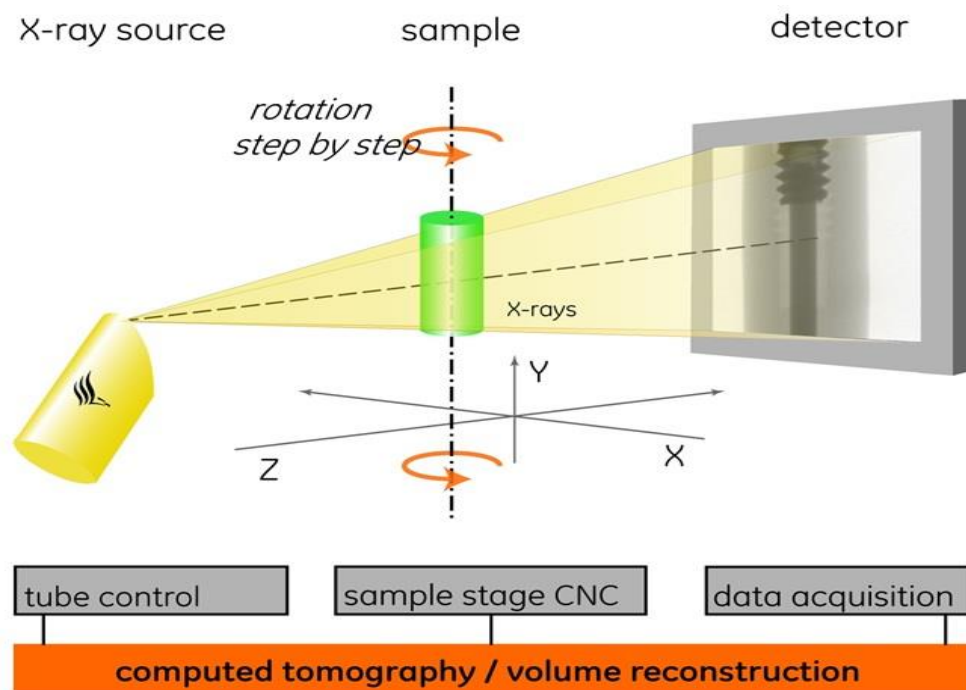


Fig. 1-3 Representation of the X-ray CT working principle ¹.

¹ Central analytical facilities (2013)

1.4.4.2 Using X-ray CT to study the effects of the tillage treatments on soil physical properties

There are a few studies which used X-ray CT to observe the changes in soil structure as affected by different practices. For instance, [Olsen and Børresen \(1997\)](#) observed that the soil layer below the ploughed soil is compacted and it had a lower number of macro-pores compared to soils under reduced tillage practices where the bulk density was not uniform. In a study by [Atkinson et al. \(2009\)](#), a CT scan was used to explore the effects of seedbed preparation on soil structure and the establishment of winter wheat. [Mangalassery et al. \(2013\)](#) used this technique to compare between no-tillage and deep ploughing in different soil types. Based on the results of these studies, the X-ray CT technique was used in the current study to observe the effects of different tillage practices and plant residue retention on the soil structure. Recently, [Millington et al. \(2017\)](#) used X-ray CT to investigate the effects of different tillage practices and traffic systems on soil structure. Also, [Blunk et al. \(2017\)](#) used this technique to demonstrate the soil-seed contact in sugar beet.

1.4.4.3 Studies on pore size and distribution in soil by X-ray CT

According to [Lugato et al. \(2009\)](#), soil pores are classified as follows: macro-pores (75-100 μm), meso-pores (30-75 μm), micro-pores (5-30 μm), ultra-micro-pores (0.1-5 μm) and crypto-pores (0.01-0.1 μm). The water flow in the soil is controlled by the pathways created by soil macro-pores ([Perret et al 1999](#)). Pore size, shape, connectivity and tortuosity and other soil pore characteristics influence the water and air movement ([Luo et al., 2010a](#)). While [Zhou et al. \(2008\)](#) noted that land use practices influence these characteristics, [Mooney and Morris \(2008\)](#) stated that soil texture also had an influence on pore characteristics. A number of researchers have explored soil pore characteristics

at a finer resolution of the X-ray CT technique. [Udawatta and Anderson \(2008\)](#) noted that cultivated lands possessed shallower and shorter pores compared to soils with grass and trees growing in. Using X-ray CT, [Mooney and Morris \(2008\)](#) studied the changes in water flow dynamics and soil pore distribution in different soil textures and reported a decrease in pore size with the decrease in soil particle size. [Luo et al. \(2010a\)](#) demonstrated soil pore characteristics (macro-porosity, network density, surface area, length density, tortuosity and hydraulic radius) are enormously impacted by soil type and land use (tillage practices).

1.5 The environmental aspects of reduced tillage

1.5.1 Chemical aspects of carbon sequestration under reduced tillage

Soil organic matter involves different components which require different decomposition time due to various physiochemical properties ([Del Galdo et al., 2003](#)). Tillage changes the aggregation process in the soil and hinders the formation of stabilised carbon fractions such as intra-particulate organic carbon ([Six et al., 1999a](#)). The decomposition of the soil organic matter depends on its type. While it takes 0.4 to 1.2 years for the labile fractions to decompose, it takes 400- 2200 years for passive pools of humic fractions located in cold temperate soil ([Lal and Kimble, 1997](#)). The ultimate product of soil organic matter decomposition is the humic acids. Between these two substances, a few of the intermediary products will be formed such as quinones and amino compounds, this process is intermediated by biological and inorganic reagents ([Stevenson, 1994](#)). Oxygen availability is the main determinant in this phenol oxidation. Cultivation practices control the oxygen availability through changing the soil porosity

(Jastrow et al., 2007). Therefore, the soil chemistry is governed by the tillage practices through their effects on the soil physical properties.

1.5.2 Biological aspects of carbon sequestration under reduced tillage

Reduced tillage forms increase the abundance and diversity of soil organisms (Roger-Estrade et al., 2010). As they improve soil aggregation, microorganisms influence the carbon recycling in the soil indirectly (Noguez et al., 2008). When reduced tillage is undertaken, Peigné et al. (2007) observed the increase of the fungi in the surface layers compared to bacteria. In aerobic conditions, fungi's carbon sequestering effects exceed the effects of bacteria. By being frequently attached to lignitic materials, fungi enhance the monomers combining to form polymers which are important constituents of the humic materials, additionally, dead fungal cells are resistant to microbial decomposition (Jastrow et al., 2007). Mycorrhizal fungi enhance soil aggregation and increase soil organic carbon. Mycorrhizae fungi take carbon from the plants into the soil when they build their bodies (Manns et al., 2007). De Rouw et al. (2010) believed that through traditional deep ploughing, plant residues get incorporated in the soil and move nearer to the decomposers, contrastingly, in reduced tillage, residues are kept initially away from the decomposers. However, in low disturbed soil in reduced tillage, fungal hyphae grow fast attaching soil and plant residues, thus decomposers and plant residues become bridged structurally (Jastrow et al., 2007). When the hyphae died, the hyphal mass will be added to the soil as a by-product of decomposition.

1.5.3 Impact of soil depth on carbon sequestration under reduced tillage

Studies which reported positive effects of no-tillage on carbon sequestration were criticised for being limited to the depth of 20 cm of the upper soil surface (Baker et al., 2007). In a meta-analysis by Mangalassery et al. (2015), it was found that carbon sequestration occurs irrespective of soil depth in both tropical and temperate conditions. The duration for which the soil was under no-tillage might be important as Angers and Eriksen-Hamel (2008) found that no-tillage caused greater organic carbon sequestration in the soil in fields which had been under no-tillage for more than 5 years in depths exceeding 30 cm. Six et al. (2002) observed a positive effect of no-tillage on carbon sequestration in depth of 50 cm following no-tillage for 20 years. López-Fando and Pardo (2011) found similar positive effects after 17 years of no-tillage.

1.5.4 Greenhouse gas emission under reduced tillage

1.5.4.1 Carbon dioxide emissions under reduced tillage

The major sources of CO₂ emissions in the soil are the decomposition of the organic matter and plant residues, and the respiration of plant roots and soil microbes (Oorts et al., 2007). CO₂ emissions increase immediately after undertaking the tillage practices with different rates according to the tillage intensity. In Denmark, Chatskikh and Olesen (2007) observed that reduced tillage caused an estimated decrease of 34% in CO₂ emissions compared to ploughing. In Canada, Ellert and Janzen (1999) reported an increase in CO₂ emissions after tillage attributing this immediate post-tillage increase to ploughing which releases the CO₂ stored in the soil pores and enhances the soil biological activities. Álvaro-Fuentes et al. (2007) observed that this immediate CO₂ emission after the soil disturbance varied according to the depth and degree of the soil

disturbance. [Licht and Al-Kaisi \(2005\)](#) indicated that the change in CO₂ emissions after tillage is more likely to be due to the change in soil structure and pore characteristics than the decomposition of the organic matter, while microbes were expected to be the main driver for the CO₂ emissions during the 10-100 days after the tillage.

Under long-term tillage studies, reduced tillage decreases CO₂ emissions due to a decrease in soil organic matter turnover. [Curtin et al. \(2000\)](#) reported 20-25% lower CO₂ emissions under no-tillage for 13 years compared to ploughing in south-western Saskatchewan, Canada. By analysing data of a 25 year long field experiment, [Bauer et al. \(2006\)](#) found that CO₂ emissions from reduced tillage were less than ploughing over the different seasons of the year. [Ussiri and Lal \(2009\)](#) compared between no-tillage and ploughing and they found after an experiment of 43 years that no-tillage caused 0.6 Mg C ha⁻¹ yr⁻¹ lower CO₂ emissions compared to ploughing when maize was grown in the United States. Contrastingly, in a long-term experiment of 32 years, [Oorts et al. \(2007\)](#) observed that no-tillage CO₂ emissions were higher than the ploughed one. The reason was thought to be a state of equilibrium in the no-tillage soil, a state which was attributed to the decomposition of old weathered crop residues.

1.5.4.2 Nitrous oxide emissions under reduced tillage

It is widely reported that N₂O increases under no-tillage ([Ball et al., 1999](#), [Chatskikh and Olesen, 2007](#), [Oorts et al., 2007](#)). A number of reasons lay behind this increase such as increase in water filled pore space, high concentration of mineral nitrogen ([Oorts et al., 2007](#)), reduction in air filled porosity accompanied with low gas diffusivity ([Chatskikh and Olesen, 2007](#)), high soil moisture content ([Blevins et al., 1971](#)) and a denser soil structure ([Schjønning and Rasmussen, 2000](#), [Beare et al., 2009](#)). [Ball et al. \(1999\)](#) also

thought that the increase in N₂O emissions when reduced tillage is undertaken could be ascribed to the anaerobic conditions caused by high bulk density and low porosity. Responding to different tillage practices, soil physical characteristics change differently in the different soil layer. Consequently, N₂O emissions are different. N₂O could be consumed by bacteria or absorbed by plants if the production point was below the soil surface. But, if N₂O is produced at the permeable surface level, then N₂O is more likely to be emanated to the above-ground atmosphere. Quantitatively, CO₂ emissions are lower than N₂O, but the N₂O warming effects is 280-300 times higher than CO₂ (IPCC, 2001). Therefore, N₂O potentially has the power to offset 75-310% of the carbon sequestered in the soil (Regina and Alakukku, 2010). In humid areas, Six et al. (2004b) noticed that when reduced tillage is undertaken for more than 20 years, N₂O effects can be nullified as the N₂O emissions were significantly lower than ploughing, whereas in dry areas, N₂O emissions were similar from both systems after this time. Similar results were also reported in other studies such as Kessavalou et al. (1998) and Chatskikh et al. (2008). The expected reason for this reduction is the increase in N₂O consumption in soil (Luo et al., 2010b). Mangalassery et al. (2014b) reported higher emissions of N₂O under no-tillage due to the wetter and denser soils as well as the increased soil microbial biomass under this management system. The estimation of N₂O emissions is still accompanied with uncertainty in many experiments due to variable spatial and temporal conditions (Chatskikh et al., 2008, Ussiri et al., 2009). Further site-specific research is required to investigate the effects of no tillage on N₂O emissions. Short term studies look fewer in number than the long term ones.

1.5.4.3 Methane emissions under reduced tillage

One of the no-tillage advantages is that it increases the absorption of CH₄ compared to other tillage treatments (Kessavalou et al., 1998, Regina and Alakukku, 2010). CH₄ absorption is the action of the methanotrophic bacteria which flourish in dense soil as there are plenty of micro sites. The activity of this bacteria increases with the increase in pore connectivity (Hütsch, 1998) and also as a result of increased bulk density when no-tillage is undertaken (Li et al., 2011). After a long term study on silty loam soil in a field of maize in the United States, Ussiri et al. (2009) found that no-tillage caused a net CH₄ uptake of 0.32 kg CH₄-C ha⁻¹ year⁻¹ against an emission of 2.76 kg CH₄-C ha⁻¹ year⁻¹ in ploughed soil. This result could be because of an increase in bulk density and pore connectivity under no-tillage. Tillage is the detrimental factor for the methane oxidisers. However, Hütsch (1998) and Venterea et al. (2005) reported that no-tillage may cause CH₄ emissions also. Overall, the CH₄ production and emissions may increase if the form of the reduced tillage enhanced the waterlogging conditions or increased the anaerobic micro-sites.

1.5.4.4 The use of static chambers to collect GHG emissions

One of the most common methods for detecting the gas fluxes from soil is the static chamber method (Livingston and Hutchinson, 1995, Pihlatie et al., 2013). The principle of this technique is to cover a known area of soil with a closed chamber that allows gas exchange to take place between the soil and the headspace inside the chamber. The change in the gas concentrations inside this headspace is measured over specific time and transformed into a flux rate which represents the soil fluxes out of that known area of soil (Pihlatie et al., 2013).

For more than 30 years, many researchers have attempted to describe the best design for these chambers ([Pedersen et al., 2010](#), [Forbrich et al., 2010](#), [Pihlatie et al., 2013](#)). While the tube-shaped chambers seem to be the most suitable, the best size has been debated as there was specific size recommended which guarantee that the gas inside each chamber is homogeneous. Thus, [Pumpanen et al. \(2004\)](#) and [Christiansen et al. \(2011\)](#) suggested installing a fan inside the chamber. Having the chamber insulated from the atmosphere is crucial for the accuracy of the gaseous measurements ([Hutchinson and Livingston, 2001](#)). The chamber size is quite important for the emission rate calculation.

Using the closed chamber method to measure the soil gas fluxes has a few concerns about the calculation of the fluxes. When the closed static chamber is placed on the soil surface, there is an assumption that the gas diffusivity from soil to the headspace increases in due course following the natural concentration gradient, but the increased gas accumulation may reduce the gas diffusion from soil into the headspace ([Nay et al., 1994](#), [Livingston and Hutchinson, 1995](#), [Davidson et al., 2002](#), [Kutzbach et al., 2007](#)). Therefore, the linear regression model which is the most common method in use, was noted to underestimate the amount of the fluxes over time ([Anthony et al., 1995](#), [Gao and Yates, 1998](#), [Livingston et al., 2005](#), [Kroon et al., 2008](#), [Kutzbach et al., 2007](#), [Pedersen et al., 2010](#)). For this reason, some other researchers have attempted to use other functions such as the exponential regression which was found to underestimate the soil emissions especially at the start of the measurement (time is zero) ([Pihlatie et al., 2013](#)). Therefore, it is suggested that checking the data and choosing the best fitting model is crucial before the full undertaking of one regression model.

1.6 The adoption of reduced tillage in the UK

Reduced tillage practices in the UK are not a new approach. In the 1970s, around 35 % of crops were established under reduced tillage practices. [Davies and Finney \(2002a\)](#) reported that this declined to 25% in 1988 due to increasing weed problems at that time. Burning straw produced from cereals and oilseeds might encourage the usage of the reduced tillage; [Carter \(1994\)](#) noted that having the residue left on the soil surface could interfere with the seed drilling process and increase the incidence of disease and pests in addition to blocking drilling machines used for crop establishment. The use of plough-based systems was observed to increase after 1993 when straw burning was banned in England and Wales ([Townsend et al., 2016](#)).

Estimates from Defra's 2010 Farm Practices Survey reveal that RT was undertaken on 44% of arable land in England, with 4% under no-tillage ([Defra, 2010](#)). A Survey on Agricultural Production Methods (SAPM) showed that RT was used in the UK on 39% of the arable land, being substantially greater than the 26% average in Europe, whereas no-tillage was estimated to be 5% in the UK, greater than the 1% in Germany and 4% in France ([EuroStat, 2013](#)). Overall, these data show that the majority of the arable land is still cultivated using plough-based systems.

The implementation of the Common Agricultural Policy in the UK requires farmers to complete a Soil Protection Review as a condition of receiving government support. In this review, farmers are highly encouraged to follow RT practices ([Anon, 2010](#)). RT is considered one of the main factors for sustainable intensification, which is a contemporary main driver for policy makers in their efforts to meet increasing food demands without increasing inputs or negative environmental impacts ([Defra, 2010](#)).

While RT uptake is increasing in the UK, major constraints to further uptake include soil type and climate (Cannell, 1985, Davies and Finney, 2002a, Morris et al., 2010). This is due to the strong link between soil type and compaction. Calcareous soils are the most suitable for reduced tillage due to their ability to mitigate compaction because of good drainage, self-mulching and stable soil structure (Davies and Finney, 2002a, Soane et al., 2012). Powlson et al. (2012) noticed that no-tillage is adopted on a small area in the UK where the predominant soil type is calcareous clay. As a result of cycles of freeze-thaw and wet-dry on uncropped land, good tilths are created and this seems to make direct seeding possible. This advantage cannot be seen on other soils.

In a review on reduced tillage in Northern Europe, Melander et al. (2013) found that when reduced tillage was applied, more herbicides were required. Deep ploughing is an effective tool for reducing blackgrass (*Alopecurus myosuroides* Huds.) which is a common weed in cereal production (Lutman, 2013). To use reduced tillage and also mitigate black grass, some farmers tend to deep till (e.g. plough) their farms every few years (3-4 years) and this is referred to as rotational ploughing (Powlson et al., 2012). Extending this concept, Townsend et al. (2016) defined an occasional deep tillage practice used in response to unfavourable weather conditions or weed problem as “strategic tillage”, as the deep tillage or plough based approaches do not take place at a fixed time point of the rotation. In this case, farmers would typically have both plough-based and reduced tillage systems on their farms and this provides them with a “mixed tillage” system; therefore, both inversion and non-inversion systems are used on the same farm, according to prevailing conditions and crop needs. Overall, with all the

recent developments in herbicides, ploughing can be replaced with a non-inversion tillage form ([Cannell, 1985](#)).

In many studies, crop yield has been reported to be either negatively or positively affected by RT practices ([Van den Putte et al., 2010](#), [Arvidsson et al., 2014](#)). This effect varies according to crop type, rotation and the depth of the tillage. In individual field studies such as [Knight \(2004\)](#) and [Verch et al. \(2009\)](#), it was reported that higher yields were recorded under reduced tillage compared to ploughing. However, tillage studies are limited and many of them are related to the time before the straw burning ban was implemented. Under these conditions, diseases, weeds and pests would have a lower negative impact on the following crop ([Graham et al., 1986](#)), and hence these previous studies are argued to not reflect the current situation of the effects of RT practices on crop yield. The machines used for the reduced tillage operations are also now much improved from those used in the 1980s. Contemporary machines are likely to be faster in achieving the soil preparation work within a suitable time window that benefits crop growth. Consequently, this improved establishment of crops may lead to greater yields (relative to plough-based systems) than those achieved in the 1980s ([Townsend et al., 2016](#)). Further studies are needed to assess the current situation.

1.7 Summary - gaps in the literature

There are a few studies looking at the effects of the different tillage practices and residue retention on crop yield and GHG emissions. Many studies looked at the effects of these practices individually, but not in combination ([Stoop et al., 2009](#), [Uphoff and Kassam, 2009](#)). These studies also did not give enough attention to the effects of the soil physical properties on GHG emissions. Limited previous studies have explored the

effects of these treatments on the net GHG emissions influenced by the soil pore structure changes such as [Mangalassery et al. \(2015\)](#). The estimation of GHG emissions is still accompanied by uncertainty in many experiments due to variable spatial and temporal conditions ([Chatskikh et al., 2008](#), [Ussiri et al., 2009](#)). Further site-specific research is required to investigate the effects of no tillage on CO₂, CH₄ N₂O emissions.

In terms of the methods, X-ray Computed Tomography (CT) with high resolution has been used instead of the destructive traditional methods to accurately investigate the change in soil structure. This method provides three dimensional data on pores and also the pore size distribution that cannot be gained by other traditional methods ([Gantzer and Anderson, 2002](#)). This is along using a number of traditional methods to estimate some of the soil physical properties including soil organic matter, moisture content, shear strength and bulk density. To detect the GHG emissions from soil and from the soil-plant system, different chambers have been designed and used to accommodate the growing plants. To reach out a large number of farmers, a postal survey method was used.

There are also a few contemporary studies which have been undertaken to explore the influence of the continuous use of reduce tillage forms on yield and the environment in humid climate conditions ([Soane et al., 2012](#), [Godwin et al., 2017](#)), and these studies are limited to specific locations or specific practices. The obvious result is that the environmental impacts of the different reduce tillage forms are variable ([Dang et al., 2015](#)). More research is required to understand the reduced tillage uptake under different climate conditions.

1.8 Research objectives

The first overall aim of this project was to investigate the effects of tillage and residue retention on soil physical properties, GHG emissions and crop yield. The second aim of this study is to understand the current situation of reduced tillage uptake by UK-farmers and any barriers to further adoption. The specific objectives of the thesis are:

- 1- To determine the effects of plant residue retention and the different tillage practices on soil pore characteristics and soil physical characteristics.
- 2- To investigate the effects of the different pore characteristics and soil physical properties as influenced by different tillage systems +/- plant residues on crop yield.
- 3- To understand the effects of the pore characteristics as influenced by different tillage systems +/- plant residues on GHGs (CO₂, CH₄ and N₂O).
- 4- To investigate UK farmer experiences of the different tillage practices and any barriers to the adoption of reduced tillage.

1.9 Thesis structure

- **Chapter 1** is an overview of the problem has been provided to be addressed in this thesis. It begins with the rationale behind this study and literature review for the previous research done in this area. A review of the methods followed in every experiment was mentioned also. Thereafter, the summary and objectives are presented.
- **Chapter 2** presents a full description of the field experiment and experimental design. It also addresses the effects of the treatments, the different tillage

practices and residues retention on soil physical properties and ultimately, the effects on crop yield.

- **Chapter 3** assesses the effects of the tillage and the residue retention on GHGs.
- **Chapter 4** is based on a survey of tillage practices in the UK and the potential to increase the uptake of reduce tillage practices.
- **Chapter 5** discusses the key results and findings of each chapter along with the main conclusions.
- **Chapter 6** has provided few ideas for future research work.

2 Chapter 2: The effect of tillage and residue retention on soil physical properties and crop yield.

2.1 Introduction

During the last few decades, the popularity of Conservation Agriculture (CA) has increased due to its advantages in conserving soil and water in areas where these resources are threatened ([Larney and Kladivko, 1989](#), [Grant and Lafond, 1993](#), [Gantzer and Blake, 1978](#), [Dao, 1993](#)). The adoption of Conservation Agriculture practices is site-specific; therefore, contemporary studies are needed in the different parts of the world to be tailored to the local conditions ([Kronen, 1994](#), [Erenstein, 2002](#), [Knowler and Bradshaw, 2007](#)).

In the temperate and humid weather conditions of the UK, the uptake of Conservation Agriculture has been limited. Reports have attributed that to farmer concerns about yield reduction over the initial years of the transition from traditional to conservation practices ([Townsend et al., 2016](#)). Crucially, many farmers believe that soil compaction would adversely affect crop productivity exacerbated by wet weather conditions ([Giller et al., 2009](#)).

The effect of tillage intensity on yield in the UK is debatable. Between 1998 and 2002, [Knight \(2004\)](#) found yield was affected by tillage regime, but the effect was different depending on the soil type. On a clay soil, the reduction was 25-40% in no-tillage in two out of three years compared to minimum tillage and ploughing. Only on light chalk-land did, all forms of non-inversion tillage practices produced the highest yields in all years ([Knight, 2004](#)). Over 9 years, [Cannell and Hawes \(1994\)](#) found that winter cereals gave

the same yields following any kind of tillage practices regardless of whether it was direct drill, shallow tillage or ploughed. However, cereals which were sown in the spring were found to yield less under no-tillage compared to ploughing. Worldwide, supporters of Conservation Agriculture insist that it can lead to higher and more stable crop yield ([African Conservation Tillage Network, 2008](#)), but there are a number of examples showing that crop yield can be affected negatively by CA, especially in the short term, i.e. during the first 2-3 years of farming management change. Farmers are, understandably concerned about this short-term yield loss ([Giller et al., 2009](#)).

Farmers believe that soil compaction resulting from changes in soil physical properties is the main reason for yield reduction ([Jones et al., 2006a](#)). Those factors are not well predicted or consistent in the different areas ([Jones et al., 2006a](#), [Morris et al., 2010](#)). This chapter aims to explore the changes in soil physical properties when influenced by different tillage practices and plant residue retention, and the impact on crop yield. The three different tillage intensities chosen were no-tillage (NT), minimum tillage (MT) and ploughing (PL) which are fully explained in Chapter 1. In addition to the effects of residue retention and removal, the comparison includes the effects of these six treatments on some of the soil physical properties from crop establishment to harvest.

Tillage practices and plant residue retention are important for seedbed establishment. The success of this stage is indispensable for a profitable and prosperous yield. Converting from traditional ploughing to reduced tillage is expected to reduce production cost and the time required for crop establishment. However, many farmers undertake deep ploughing on their farms to incorporate plant residues, bury weeds, create a seedbed that provides an ideal seed-soil contact and mitigate soil compaction,

allowing the flow of water and nutrients and enabling the plant roots to penetrate and flourish alongside the soil microbial communities ([Hermawan and Bomke, 1997](#), [Bengough et al., 2006](#)).

Tillage practices and residue retention have an important impact on soil chemical, biological and physical properties through influencing soil aggregate size and shape. The aggregates control the soil pore environment including air, water, and temperature. Different crop types and varieties respond to changes in soil aggregate size in different ways according to the different growth stages. For example, during seed germination, soil aggregate size is an influential factor for the germination process and initial root development ([Braunack and Dexter, 1989](#)) due to the effect of tillage system and plant residues on soil aggregate formation ([Schjønning and Rasmussen, 2000](#)).

Tillage system has a direct effect on soil pore characteristics and soil aggregation. The optimum aggregate size in the seedbed is between 1-3 mm which is expected to create ideal pore sizes for cereal crops such as wheat, barley and oat ([Kvasnikov, 1928](#)). Larger aggregates create larger pores, consequently, soil-seed contact will be less than optimal ([Dexter, 1986](#), [Atkinson et al., 2009](#)). Rolling is a process which follows seed drilling to improve the seed-soil contact and thereby germination and emergence ([Håkansson et al., 2002](#)). Soil structure characteristics and other soil physical properties are extremely important for root distribution and their ability to take up water and nutrients ([Pardo et al., 2000](#)).

2.1.1 Soil compaction

Soil compaction is the physical consolidation of the soil particles as a result of applying force on the soil surface. Soil compaction can be seen in many ways such as reduction

in soil porosity and reduced water and air movement in the soil. Ploughing is one of the factors to mitigate soil compaction. However, repeated ploughing down to the same depth without following suitable crop rotations can create a “plough pan” just below the tillage layer (Doan et al., 2005).

Soil compaction has a direct effect on root growth (Awadhwai and Thierstein, 1985, Aubertot et al., 1999, Dexter, 2004). Compaction can hinder root development by affecting these factors, for which roots could respond by changing their behaviour, for example ceasing growth, growing near to the soil surface only or having thick and short roots (Bingham and Bengough, 2003, Clark et al., 2003). Soil air and moisture content are necessary for root respiration and growth. Any mechanical restriction would limit the movements of air, water and minerals making them less affordable for the plants (Larney and Kladienko, 1989, Oussible et al., 1992). Soil compaction in the surface soil layer has adverse impacts on plant growth and yield (Hammel, 1989, Mahboubi et al., 1993). Previous studies have shown that soil physical and biological factors influence the yield of cereal crops when they are grown under NT due to soil surface compaction (Cornish and Lymbery, 1987, Kirkegaard et al., 1994, Simpfendorfer et al., 2002).

2.1.2 The impact of plant residue retention on the soil surface

The aim of the plant residue retention is to protect the soil surface from rainfall impact, increase infiltration rate, reduce erosion and increase soil organic matter content (explained in the literature review chapter). Organic matter binds soil particles encouraging soil aggregation and increases the amount of nutrients available to the plants. It is expected that soil organic matter increases soil temperature and water

content from establishment to maturity (Sprague and Triplett, 1986, Kumar and Goh, 1999).

Plant residue retention may lead to yield reduction due to slower germination caused by the cold residue-cover soil (Al-Kaisi, 2002, Morris et al., 2010). Slow germination is the result of the formation of thick clumps of stubble which might lead to around 50% reduction in in the crop yield (Harper, 1989). Furthermore, the plant type whose residues are retained on the soil surface is important. Doan et al. (2005) found that addition of legume residues; such as *Pisum aestivum*, had a better effect than the addition of *Brassica napus* or *Triticum sativum* on lessening the soil and releasing the penetration resistance. This could be because of the different time required for decomposing different plant materials.

2.1.3 The impact of different tillage systems and residue retention on selected soil physical properties

2.1.3.1 Soil penetration resistance

Previous researchers observed a higher soil penetration resistance under reduced tillage forms compared to ploughed ones in the tillage layer (Doan et al., 2005). However, in addition to the tillage system, penetration resistance is affected by other factors. In no-tillage soil, soil penetration resistance was correlated with the soil sand percentage, soil moisture content and depth, but it was correlated with clay percentages and depth in the PL plots (Doan et al., 2005). Thus, the extent of soil compaction is dependent on several factors, and not the tillage system exclusively.

Soil penetration resistance levels affect plant growth in the different growth stages. For example, wheat plants can germinate when the soil strength is <3.0 MPa and stems can elongate if soil strength is <2.3 MPa, but 1.7 MPa and 0.8 MPa are the maximum limits which would stop the coleoptile growth and plant emergence respectively ([Jakobsen and Dexter, 1987](#)). Though, plants have different limits for soil strength, however, [Bengough and Mullins \(1990\)](#) observed that plant growth stagnated when the penetration resistance exceeded 5 MPa.

2.1.3.2 Soil bulk density

Bulk density differs according to tillage intensity and the period of time over which the same systems have been applied. Several studies have not recorded significant effects for the tillage systems on bulk density ([Rusu et al., 2009](#), [Calegari et al., 2010](#)), but others such as [Ferreras et al. \(2000\)](#) and [Moraru et al. \(2013\)](#) found that no-tillage increased bulk density compared to PL. In a comparative study between different cultivation practices, [He et al. \(2009\)](#) found that bulk density in no-tillage was greater than PL during the first 4 years of consecutive no-tillage undertaking, but after that smaller bulk density was recorded in no-tillage. This suggests that the effect of the no-tillage on increasing soil bulk density is immediate, but does not last for long.

Sometimes, ploughed soils may have highest bulk density compared to reduced tillage forms. This incline could be attributed to two reasons: (1) The heavy machines used usually for ploughing ([Mamman and Ohu, 1998](#)) and (2) the effect of the wet weather conditions on consolidation/compaction of plough layer ([Indoria et al., 2017](#)).

Plant residue retention reduces soil bulk density due to the fact that plant residues replace the heavier soil mineral particles. Additionally, the organic matter is expected to increase soil pore sizes and numbers in the short and long term. These effects have been shown in different soil types and accompanied with different tillage practices including no-tillage ([Shaver, 2010](#), [Indoria et al., 2017](#)). [Li et al. \(2007\)](#) found for a silt loam soil under no-tillage with plant residue retention could reduce bulk density.

2.1.3.3 Soil moisture content

Soil moisture content is expected to increase as a result of both residue retention and reduction in the tillage intensity. Plant residues form a mulch which protects the soil surface from solar radiation and reduces air traveling through the soil pores reducing the evaporation rate. Plant residues increase the infiltration rate as a result of reducing the runoff of water on the soil surface ([Ghosh et al., 2015](#)). In sandy soil, organic matter increases water holding capacity. Soil organic matter also enhances the formation of large water-stable soil aggregates which resist water and soil erosion ([Puget et al., 1995](#), [Balabane et al., 2005](#), [Corsi et al., 2012](#)).

With regard to the tillage practices, no-tillage increases soil moisture content. This is more important in areas where water is a constraint for rain-fed crops ([Acharya et al., 1998](#), [Sławiński et al., 2012](#)). [Shaxson and Barber \(2016\)](#) stated that moisture content under no-tillage is higher than plough attributing that to higher porosity and less runoff under no-tillage. Comparing between the different tillage practices, [Alvarez and Steinbach \(2009\)](#) reported that no-tillage increased the water content by 13-14% compared to other tillage practices in 35 trials in Argentina. It is believed that soil water content increases when soil structure is improved as a result of high organic matter

accumulation, increased infiltration rate and decreased evaporation ([Thierfelder et al., 2005](#), [Bescansa et al., 2006](#)). A few other researchers did not find differences in soil moisture content between the different tillage forms near to the soil surface in different ecological regions due to soil compaction accompanied by reduced infiltration rate under no-tillage ([Hill, 1990](#), [Thorburn, 1992](#), [Vyn and Raimbult, 1993](#), [López et al., 1996](#)).

2.1.3.4 Soil structure

When individual soil particles (sand, silt and clay) are bound by a binding agent such as organic matter, they form soil aggregates which get larger as more particles are bound over time. Soil structure is the architecture formed by these aggregates and other materials in the soil. Soil aggregates are important for assessing the stability of the soil structure against the different stress conditions including tillage, irrigation, drought etc.

According to [Govaerts et al. \(2009\)](#), after 15 years of experimenting NT accompanied with plant residue retention, the dry aggregate size distribution improved compared to ploughing. Under different ecological conditions [Lichter et al. \(2008\)](#) and [Govaerts et al. \(2009\)](#) found that NT and residue retention increased the aggregate size and improved soil structure stability. The reasons for this are the increase in the organic matter content from plant residue retained and from the reduction in organic matter oxidation resulting from NT itself. NT also enhances the growth of mycorrhizal hyphae in the soil. Organic matter, mycorrhizae and other organisms are agents which encourage the increase in the aggregate stability by the continuous gluing of more soil particles ([Bronick and Lal, 2005](#)).

Ploughing stifles any improvement in the soil structure and damages any improvements that could have happened previously. The multi-pass cultivations break down the macro

and micro-aggregates. Ploughing redistributes organic matter in the soil, preventing the aggregation process (Six et al., 2002).

There is a positive linear correlation between soil organic matter and soil aggregate stability (Carter, 1994). Soil organic matter increases the aggregate stability making the soil resistant to extreme conditions such as irrigation and heavy rain (Blevins et al., 1998). Overall, under NT and the retention of plant residues, aggregate stability is increased as a result of the following:

- 1- The integration between soil particles and aggregates with plant residues, as a result of leaving the plant residues on the soil surface.
- 2- The decomposition of organic matter enhances the aggregation process.
- 3- The flourishing and abundance of microbes and fungi hyphae, as a result of the soil minimal disturbance.
- 4- The soil is expected to be denser and this increases the resistance of the soil structure to change. In other words, soil structure is expected to be more stable.

In addition to these benefits, under intensive tillage practices, the population of the micro and macro fauna are decreased compared to any reduced tillage forms. This would slow down the soil aggregation process (Six et al., 2004a).

Many researchers have attempted to model soil physical indices (e.g. Da Silva et al. (1994), Tapela and Colvin (2002) , Pagliai et al. (2003), Leao et al. (2006) and explore the relationships between soil and crop establishment (e.g. Atkinson et al. (2007)). However, only few studies have explained the link between physical properties and crop yield (Millington et al., 2017).

A review of the literature on CA shows that many studies have explored the effects of residue retention only (Turmel et al., 2015) or the different tillage practices only on soil properties and yield (Pittelkow et al., 2015b). The effects of the two factors are rarely found. The effects of the different practices only on soil and seedbed have been well researched in the past, but more comparative studies are needed to explore how the soil physical properties change over time as influenced by different tillage intensities and the plant residues together.

The aims of this chapter were to:

1. Describe changes in soil physical properties as affected by different tillage and residue management practices over a two-year period.
2. Compare the effects of the different tillage and residue management practices on crop establishment, growth and yield.

2.2 Materials and methods

2.2.1 Study site

A field experiment was established in September 2014 at the University of Nottingham Farm, Sutton Bonington Campus, Loughborough, Leicestershire UK (52.841806, 1.254035). The farm is provided with a weather station. The preceding crop was winter wheat which was harvested in August 2014. The field was previously in a rotation of winter wheat, winter wheat and barley. The crop in the first year of this experiment was second winter wheat, followed by triticale in the second year. The field size is 4.11 ha, but the experiment took place on around 2 ha located at the centre.

2.2.2 Baseline measurements

After harvesting the winter wheat, baseline measurements were carried out in the field in August and September 2014. The aim of these measurements was to confirm the soil physical properties in the field before the start of the experiment, in order to check for homogeneity in the soil structure and assess the level of within-field variation. The three baseline measurements performed were:

1. Soil structure: 6 soil core samples (5 cm diameter and 30 cm length) were collected for X-ray Computed Tomography imaging. The locations of the sampling were chosen randomly.
2. Soil organic matter (SOM): 36 bulk soil samples were collected from the upper 0-30 cm of the soil surface and analysed using a loss on ignition (LOI %) method. Samples were collected randomly from the field from areas which were around 10 m from each other.
3. Particle size analysis test to explore the predominant soil texture in the field. A total number of 36 bulk soil samples were collected from the field from the upper 10 cm of the soil surface.

2.2.3 Experimental design

The experimental design was a split plot design with residue retention on main plots. The field was divided into 4 blocks, which were each divided into 2 main plots and then further subdivided into 3 subplots. The subplots were 12 m long and 9.6 m wide with 2.4 m gap in-between. The discard area which separated each block was 12 m. The experiment was surrounded by a 12 m discard area from all sides. The experimental design is outlined in [Fig. 2-1](#).

2.2.4 Treatments (Residues and Cultivation)

The main plot treatment was residue retention. In the first year, all the straw of the previous crop was baled and then 6250 kg ha^{-1} was chopped and spread on the soil surface prior to the seedbed preparation. In the second year, the straw was chopped and retained during harvest on the residue retention plots and removed from the remaining plots. Cultivation practices were applied to the subplots and included 3 different tillage systems:

- 1- Conventional ploughing (PL): which included a single pass of a 4 furrow *Lemken Jewel* plough (7 meter, furrows set at 35 cm each), followed by pressing with a *Lemken VarioPack* 110 furrow press. The depth of the ploughing is 30 cm.
- 2- Minimum tillage (MT): using a *David Brown 9 leg grubber* cultivator which disturbed soil surface down to the depth of 10 cm. The cultivator is 250 cm wide with a leg spacing of 25 cm.
- 3- No tillage (NT): in which no soil cultivation was performed before the drilling which means that soil was left un-cultivated before seeding.

Thereafter, crop seeds were sown with a *4m Horsch Sprinter winged tine drill* followed by rolling across the whole area. To maintain healthy crop growth, a programme of pesticides and fertilisers was followed in both years. In the first year of the experiment, the residue spreading and cultivation took place on 15 September 2014. The field was sown with second winter wheat (cv. Revelation) on 10 October 2014 at a seed rate of 318 seed m^{-2} . Alongside the seeds, 5 kg h^{-1} of slug pellets were applied. On 17 March 2015, the field received 50 kg ha^{-1} nitrogen plus 25 kg ha^{-1} Sulphur Trioxide (SO_3). The field received 190 kg ha^{-1} of ammonium nitrate on 05 May 2015 in the form of Nitram.

In preparation for the second year of triticale, cultivation took place on 09 September 2015. The field was sown on 23 October 2015 at a rate of 400 seed m⁻². Fertilisers added were 250 kg ha⁻¹ (N.P.K.S= 29:0:0:20) on 11 March 2016. Harvest occurred on 10 August 2015 and on 9 August 2016 for winter and triticale respectively. Over the two years the field was treated with different herbicides including; Backrow 0.2 L.ha⁻¹, Liberator 0.6 L.ha⁻¹ and Hurricane 0.1 L.ha⁻¹ on 20 October 2014, Atlantis 0.4 kg.ha⁻¹ and Kantor 0.15 L.ha⁻¹ on 19 March 2015 and Rodeo 2.5 L.ha⁻¹ and Mixmate 0.21 L.ha⁻¹ on 01 Nov 2015.

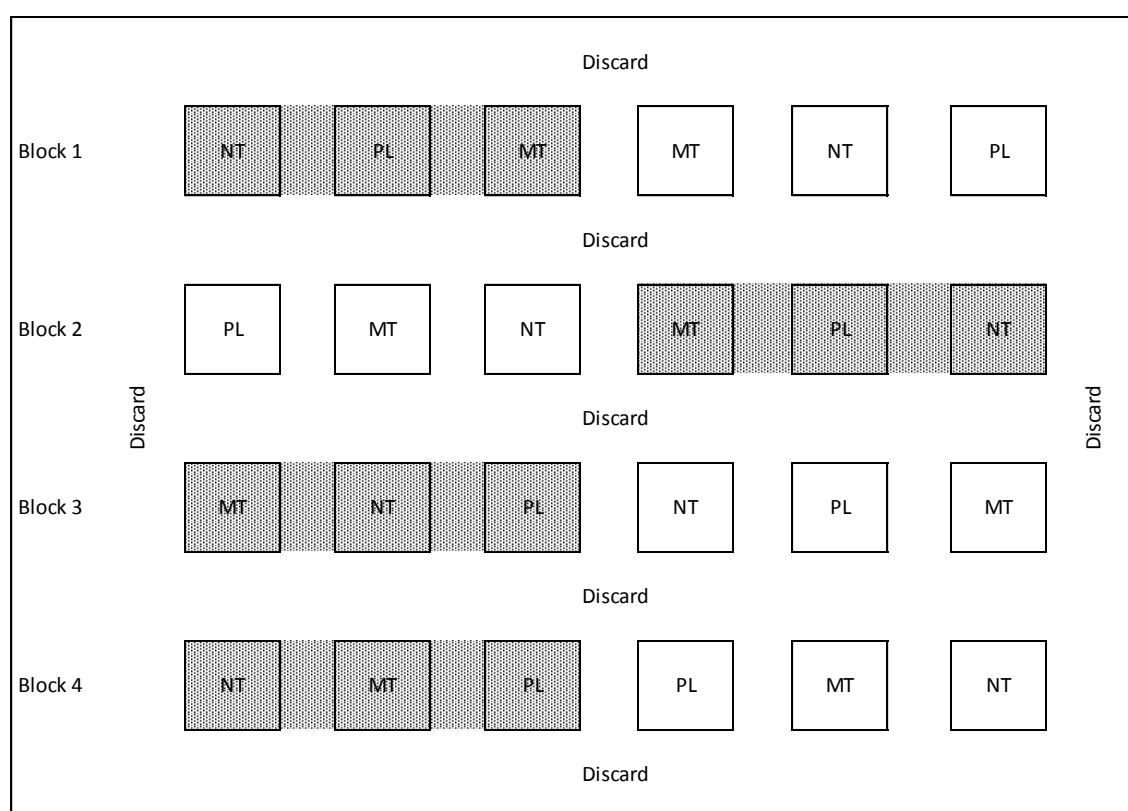


Fig. 2-1. The experimental design outline for the field experiment. NT: No tillage, MT: minimum tillage and PL: conventional ploughing. The grey areas indicate the main plots where residues were retained.

2.2.5 Measurements

2.2.5.1 *Soil physical properties*

Measurements of soil physical properties started in December 2014, two months after the crop was sown. The same measurements were repeated in March, June and August 2015 when harvest occurred and with the same frequency during the 2015-6 season.

Evaluation of the soil physical properties included measuring the soil penetration resistance (PR), bulk density (BD), shear strength (SS), soil organic matter (SOM) and soil moisture content (SMC). Soil samples were collected from each plot after leaving a 1 metre buffer zone to avoid edge effects. Positions were avoided in each plot if large stones were found or on tramlines. Gravimetric water content and soil organic matter were measured in the tillage layer of the top 30 cm of the soil. Samples were collected from 3 different depths within this layer; 0-5 cm, 5-15 cm and 15- 30 cm with five replicates from each plot. This enabled the exploration of the effects of treatments on the different depths, as well as how this affected crop growth and yield. To assess the soil penetration resistance in the top 30 cm of the soil with three replicates in each plot, two devices were used. On December 2014, a Findlay/Irvine Ltd. 'Bush' cone soil penetrometer was used. This device measured the penetration resistance through the soil profile at intervals of 3.5 cm down to 30 cm. Measurements were recorded in kilogram-force per square centimetre (kgf cm^{-2}) and were converted to MPa. For the rest of the soil penetration resistance measurements, a CP 40 II cone penetrometer (Rimik, Australia) was used. Using this device, the PR was recorded every 1 cm. Measurements were recorded in kPa and were converted to MPa.

Soil shear strength was measured using a Pilcon 120 kPa hand vane 30 X 16 mm (Pilcon, New Zealand) which was inserted into the soil surface down to 5 cm depth and rotated until the soil failed. For each time point, three replicates per plot were taken. To assess the bulk density, 3 replicates per plot of undisturbed 141 cm³ core samples from the 4 cm of the topsoil were collected and weighed after oven drying for a period of 24 hours to constant weight at 105 °C. To collect those samples a special metal ring prepared for this purpose was used. The ring had a diameter of 6.7 cm, a height of 4 cm and a volume of 141 cm³. It was pushed into the soil surface before a wooden board was placed on top and hammered gently to ensure the even and equal pressure so as not to compact the soil samples to be collected.

2.2.5.2 Soil structure assessment

Although the tillage treatments were expected to affect the whole soil profile, [Lipiec et al. \(2007\)](#) found that those differences are more pronounced at depth of 0–10 cm than at lower depths. For this reason, the changes in the soil structure only in the top 10 were investigated.

2.2.5.2.1 Sampling and sample storage

Intact samples of the soil surface in each plot were collected on a 3 month basis, during the first year of the experiment at the same time when soil physical properties were measured (December 2014, March 2015, June 2015 and August 2015) and at the end of the second year (August 2016). To collect the samples a 30 cm metal auger of 4.5 cm diameter was used. The auger was pushed down to 30 cm of the soil surface with transparent PVC sleeves inside. The auger was pushed into the soil using the weight of the person collecting the samples and also using a hammer when the soil was

compacted or hard to penetrate. A plastic lid was used for each core sample to cover the column and to prevent moisture loss. All columns were labelled, placed into labelled plastic bags and wrapped with several layers of cling film. These samples were stored at constant temperature of 4 °C until scanning, which took place within one week.

2.2.5.2.2 X-ray Computed Tomography

The upper 10 cm of the samples were scanned with X-ray CT scanner, Phoenix X-ray system (GE Sensing and Inspection Technologies GmbH, Germany). The X-ray tube had maximum voltage of 240 kV and a maximum output of 15W. The spatial resolution range was between 5 and 150 µm.

2.2.5.2.3 Sample preparation and acquisition of CT data

The X-ray beam used was generated by passing a high energy current over a tungsten target. The samples were placed carefully in the scanner ensuring that they were firmly fitted to prevent any movement of the sample during the scan. To ensure the acquisition of good quality images, within a reasonable time period, the energy levels and the current were adjusted after placing the intact sample on the stage. This was done by looking at the histogram to ensure that the centre part of the core (the densest part), had a value of $\geq 20\%$ of the dynamic range of the detector. To improve the image quality, a copper filter was used to control the incident X-ray beam. To get high quality images, the position of the detector in the X-ray gun was tested. After choosing the most suitable scanning parameters including the energy detector, timings, spin and resolution, the sample was removed from the stage for the X-ray signals to be calibrated.

Offset and *gain* calibrations were undertaken. During the gain calibration, the X-ray was switched on during the scanning, whereas it was switched off during the offset

calibration. The calibration aimed to standardise the detector with respect to X-ray signals being generated. It was considered as a baseline to which all other sample scan data were subtracted. After the process of the calibration, the sample was returned to the sample stage. Finally, the CT-scanning was undertaken at energy levels of 130 kV and a current of 110 μ A. The soil samples were placed vertically and around 1500 images at a resolution of 62 μ m were collected within 12 minutes of scanning for each sample.

2.2.5.2.4 Image reconstruction

After scanning the samples, image reconstruction was performed for the data obtained. The *datos|x* software (GE Sensing and Inspection Technologies GmbH, Germany) was used for this process. This software converts the raw projection intensity data to a range of grey scale (12 bits) CT numbers. This scale corresponds to the coefficient of X-ray attenuation. This coefficient represents X ray energy, density and atomic number.

2.2.5.2.5 Artefacts

In *datos|x*, the scan optimiser option was used to compute the difference between the first and last image, the value after that was accepted. This step is important as it reduces any artefact generated after any movement of the sample during scanning.

2.2.5.2.6 Beam hardening

Beam hardening can affect the scanning quality by making a centre of a sample less bright than the edge of the samples. Before the scan, the X-rays were pre-hardened by placing a copper filter of (0.1) thickness in front of the X-ray tube to avoid this artefact. At the middle of the core samples, beams can be attenuated easily ([Mangalassery et al., 2014b](#)).

2.2.5.2.7 Image analysis

To investigate the differences in the pore morphology characteristics, the software ImageJ was used (Rasband, 2002). In every image, the pores near the edge of the samples were excluded in the reconstructed CT images by defining a rectangular region of interest. The analysis was performed on 1100 images, starting from the top to the bottom of every sample. As the samples were collected at different times, a suitable analysing methodology was required for each set of samples. This is due to the aging of the CT filament which causes variations in image brightness. To optimise this process several filters and different enhancement techniques for reducing the noise in the images were tested. In some instances, the image quality was so high (due to a new filament), filters were not needed such as for samples collected in December 2014, June 2015 and August 2015 (Table 2-1).

Table 2-1. The threshold and filtering methods used during the analysis of the CT-scan images.

Sampling date	Filters	Threshold algorithm
Baseline samples	Median	Iso data
December 2014	No filter	Renyiropy
March 2015	Median	Renyiropy
June 2015	No filter	Li
August 2015	No filter	Li
August 2016	Median	Manual (33.88)

The images were converted to an 8-bit gray-scale image. A thresholding method with a suitable automated or manual algorithm was performed to differentiate between pores and solids. However, for the samples collected on the same day, the same threshold method was always undertaken. Thresholding is a process through which a gray-scale image is segmented into a binary image. This is after choosing a point of segmentation on a histogram.

For the baseline samples and the four following sets of samples collected in the first year, automatic threshold algorithms were used. However, in the samples collected in August 2016, the automatic threshold algorithm overestimated the porosity due to increased image noise. For this reason a manual threshold method was developed based on testing a range of different algorithms on several images from different samples.

The samples were collected on the same day, but they were scanned over two days (16 August 2016 and 07 September 2016) because of the time required. This was taken into consideration when the decision was made regarding the selected threshold method. Samples from both days were examined. During this process the minimum, the maximum and a median value were chosen. Below the minimum value and above the maximum value, the threshold would have been clearly unsuitable. The optimum range was from 27 – 37 from which an average of 33.88 was applied.

After acquiring the binary images, the noise was reduced by the “remove outlier” tool in ImageJ. ImageJ generates statistics describing the characteristics of every single pore through the option “analyse particles”. The information obtained was for number of pores, average pore size, porosity, surface area and circularity of pores. VGStudio Max was used to investigate the percentage of connected pores.

From the pore sizes provided, the coefficient of uniformity (PSD_{cu}) was calculated. The coefficient of uniformity is a numerical illustration for the differences between large and small pores. It provides a ratio of the size of pores at a 10% and 60% total porosity of the sample, the larger the ratio the greater the number of larger pores ($PSD_{cu} = d_{60}/d_{10}$) (Kézdi and Rétháti, 1974, Atkinson et al., 2009).

2.2.5.3 Crop and yield measurements

Plant population, Normalized Difference Vegetation Index (NDVI) and combinable crop yield were recorded in both years. Plant population was captured at the beginning of the stem elongation stage when the first node was detected ([Zadoks et al., 1974](#)). This time was chosen as the crop would have passed the cold weather in winter which could reduce plant population in all plots. To count the plants, a 0.72 m² (1.2 m * 0.6 m) quadrat was used. The quadrat was placed randomly inside the plots to avoid bias, but at least 1 m away from the edges and soil measurements took place. Crop yield was estimated at the end of every season by harvesting ca~ 20 m² (10 m * 2 m) of undisturbed area along each plot using a sample plot combine.

Spectral reflectance was measured using a spectroradiometer (Green-Seeker Hand Held Crop Seeker, Model HCS-100; Trimble Navigation Limited, CA, USA), at different growth stages during the season. Five NDVI measurements were recorded during both years on dates when all wheat and triticale were near or at growth stages: 39 (stem elongation), 49 (booting), 69 (flowering), 75 (milk development) and 83 (dough development) ([Zadoks et al., 1974](#)).

Normalized Difference Vegetation Index (NDVI) measures the plant canopy including differences in chlorophyll content, biomass production and leaf green area factors which influence the yield production. NDVI also indicates how the crop is responding to the treatments in the different stages of the growth ([Lopes and Reynolds, 2012](#), [Hazratkulova et al., 2012](#)). Readings were taken on each plot by using the Green Seeker. The average spectral reflectance reading recorded every seven meters on transect. The process was repeated three times for each plot. When the device is held approximately

at a distance of between 0.6 m to 1 m from the plant illuminated surface, the sensor measures 0.6-1 m spot constantly. During the measurement, the device was kept perpendicular. The sensor unit has self-contained illumination in both the red (650 ± 10 nm full width half magnitude (FWHM)) and near infra-red (NIR) (770 ± 15 nm FWHM) bands. The green seeker measures fraction of the light reflected from the sensed area. These fractions are used within the device to calculate the NDVI from this formula (Sharma et al., 2015):

$$NDVI = \frac{NIR - VIS}{NIR + VIS}$$

NIR: the fraction of emitted NIR radiation returned from the sensed area (reflectance).

VIS: the fraction of emitted visible red radiation returned from the sensed area (reflectance).

2.2.5.4 Statistical analysis

Using GenStat 17th Edition, analysis of variance (ANOVA) was applied to explore the effects of the different tillage practices and residue retention on soil properties and crop growth. Treatment structure was (cultivation*residues) and the block structure was as block/residues. To account for interdependence of the soil property data over time, repeated measurement model in ANOVA was used to consider the data at different time points (Sommer et al., 2014). Prior to the statistical analysis, the distribution of every variable was checked to ensure that they were normally distributed using Shapiro-Wilk test for Normality in GenStat. For soil organic matter and soil moisture content, a repeated measurement model was performed, but depth was added as a factor. For the analysis of the penetration resistance at a single time point, spilt- split- plot design model was performed. The treatments were residues*cultivation*depth. The block structure was block/residues/cultivation.

Correlation matrix and regression model

Crop yields are affected by soil physical properties including strength, resistance, water content, density and soil structure characteristics such as porosity, connectivity, average pore size and pore size distribution. Yield is more likely to be affected by a group of factors rather than a single factor. For this reason, a correlation matrix and a multiple linear regression model were developed to identify the relationship between the yield and the soil physical properties over the duration of the experiment. This helps to understand how different tillage practices and plant residue retention could affect soil physical properties and ultimately grain yield.

The correlation matrix included the results of the repeated measurements that had been collected every two or three months depending on the time of the measurements. Soil moisture was added based on an average of the three depths and also based on the moisture in the top 5 cm of the soil surface only. All the measurements up to harvest were included. For the results of penetration resistance, an average of every 10 cm was included in a way that the relationship between the yield and the penetration resistance in the depth 0- 10 cm, 10- 20, and 20– 30 cm would be explored. The bulk density and shear strength in the top 0-5 cm of the soil surface were considered. Soil structure characteristics were included as an average of every sample collected from the upper 10 cm of the soil surface.

On the level of ($P < 0.1$) according to the Table of Critical Values, Pearson Correlation, factors were included in a Generalised Regression Model ([Petrie and Watson, 2013](#)). The regression model was designed from the triticale yield, as it was affected significantly by the treatments, and those significantly influential factors. Factors which

did not have a significant effect on yield were dropped off the model based on the P -value of each factor. The factor with the highest and insignificant P -value ($P>0.05$) was dropped off first. As a result of this technique, the most important predictors remained.

2.3 Results

2.3.1 Baseline measurements

2.3.1.1 *Soil texture*

The sand content in all the samples was high ranging from 73.5% to 83.6%. The clay content ranged from 12.3% to 16.6%. The silt content varied between 2.0% to 12.1%. Consequently, the soil type was classified as sandy loam in all the collected samples. The variation in the soil particles did not affect the classification of the soil. Therefore, the soil texture in the field was considered homogeneous and was not expected to affect the attained results.

2.3.1.2 *Soil structure*

The analysis of the six samples collected from the different positions in the fields showed that the soil structure in the field was more variable than the soil texture, but this variation was not high compared to the mean of the value in each parameter ([Table 2-2](#)). At the resolution of 0.062 mm, the average number of pores was 269 ± 45.22 pores (mean $\pm$ SD). The porosity was 27.46 ± 1.77 %. The pore size in all samples was normally distributed between 0.5 and 3 mm² log₁₀.

Table 2-2. Results of baseline measurements of some aspects of the soil structure.

Sample	Number of pores	Porosity %	Pore size distribution (60:10)
Average	269	27.46	110.00
SD	45	1.77	42.62

2.3.1.3 Soil organic matter

The average soil organic matter was $5.68 \pm 0.064\%$ (mean $\pm$ SD). The lowest value was 4.77% and the highest value was 6.36%.

2.3.2 Weather conditions

Overall, total in-crop rainfall in 2014-5 was 528.4 mm and 718 mm in 2015-6. From November until April, the rainfall was 284.8 mm during 2014-15 (wheat) and 423.6 mm during 2016-17 (triticale). In June 2016, the rainfall was 153 mm, approximately three times more than what it was in June 2015 (50 mm) (Fig. 2-2).

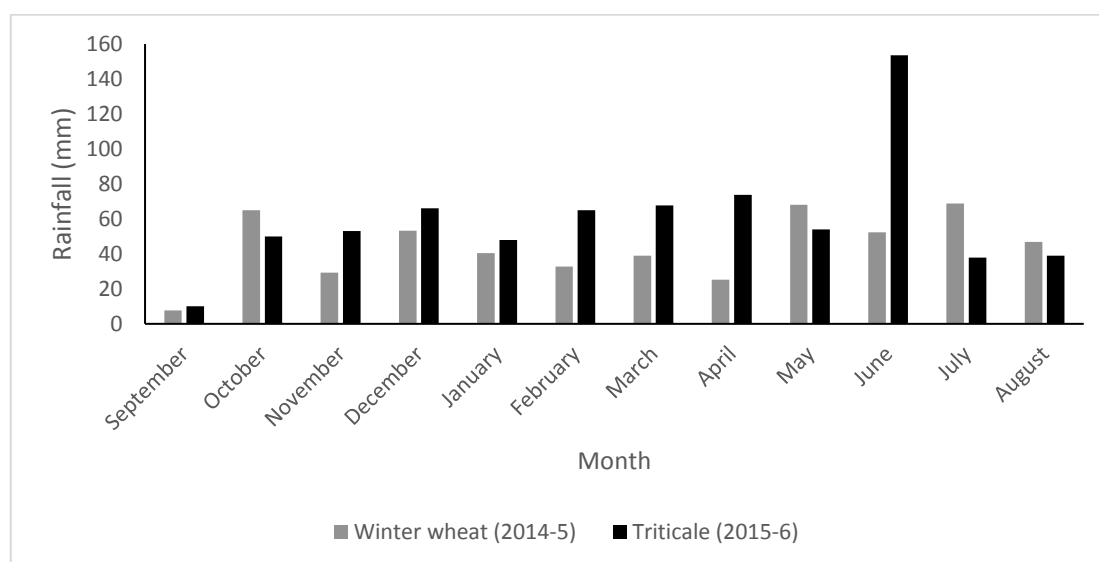


Fig. 2-2. Total monthly rainfall during field experiment in 2014, 2015 and 2016.

Fig. 2-3 shows the average monthly air temperature in the field in Sutton Bonington between 2014 and 2016. The average in 2014-5 was 9.6 °C which was slightly less than

the following year at 10.1 °C. Overall, the differences in the temperature of the two years are small.

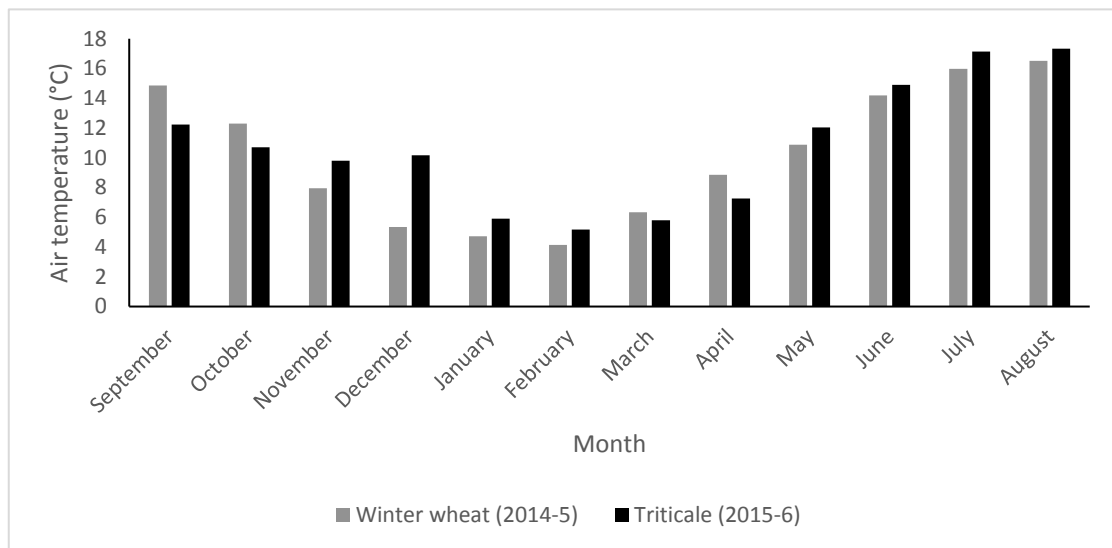


Fig. 2-3. Average monthly air temperatures during field experiments in 2014, 2015 and 2016.

2.3.3 Soil physical properties

2.3.3.1 Soil bulk density

The soil bulk density in the upper 5 cm of the soil was significantly affected by the different tillage systems during the two years of the experiment while residue retention did not have a significant effect. The average bulk density was 1.31 g cm⁻³ in NT, 1.28 g cm⁻³ in PL and 1.21 g cm⁻³ in MT (Table 2-3). The difference between NT and PL was marginal, but MT was less than NT and PL ($P < 0.001$).

Although the bulk density was not significantly different over time, the overall trend was different between the first and second year (Fig. 2-4). During the first year when wheat was grown, BD was highest in PL. In December 2014 when the measurement started, there was no significant difference between NT and MT, but there was between PL and both of NT and MT. During the second year, when the triticale was grown, BD was significantly higher in NT. With an increase in the crop age, BD in NT increased to a peak

of 1.34 g.cm^{-3} in June 2016. Overall, the lowest BD values were observed in MT significantly over the course of the experiment. By the end of the study, soil bulk density increased in NT from 1.25 g.cm^{-3} to 1.33 g.cm^{-3} , whereas it decreased in MT from 1.19 g.cm^{-3} to 1.18 g.cm^{-3} and in PL was the same as it was at the beginning of the experiment (1.31 g.cm^{-3}).

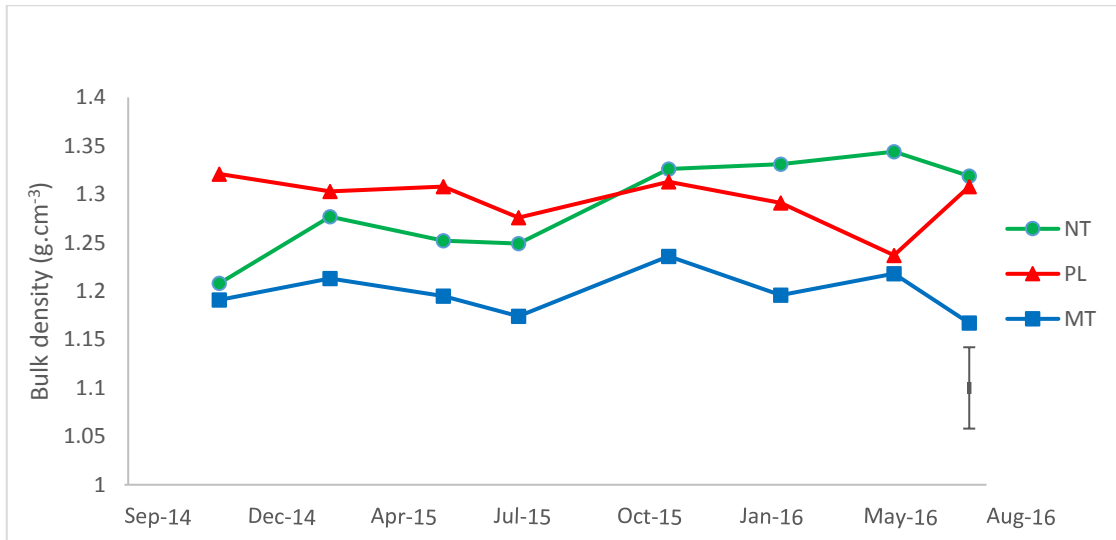


Fig. 2-4. Dry soil bulk density, 0-5 cm, over two years; through the growing season of wheat and triticale, as influenced by cultivation practices (NT: no tillage, MT: minimum tillage, PL: ploughing). Error bars represent S.E.D. (85.43 d.f.). Each year, cultivation practices and harvest were taken place in September and August respectively.

2.3.3.2 Soil shear strength

Soil shear strength was significantly influenced by both the cultivation system and time ($P < 0.001$) as presented in (Fig. 2-5). There was also a significant interaction between time and cultivation ($P < 0.05$). NT regime led to the strongest soil with an average shear strength of 34.0 kPa compared to 27.4 kPa in MT plots and 26.0 kPa in PL plots (Table 2-3). Soil shear strength was the lowest in PL plots during the whole two-year experimental period. However, the magnitude of the difference ranged from 1 kPa between NT and PL in August 2015 to 14 kPa in December 2015. The lowest shear strength values were found at the beginning of the experiment in December 2014. The

peak shear strength values were observed in June 2015. There was a significant difference at all time points except between March 2016 and June 2016 measurements.

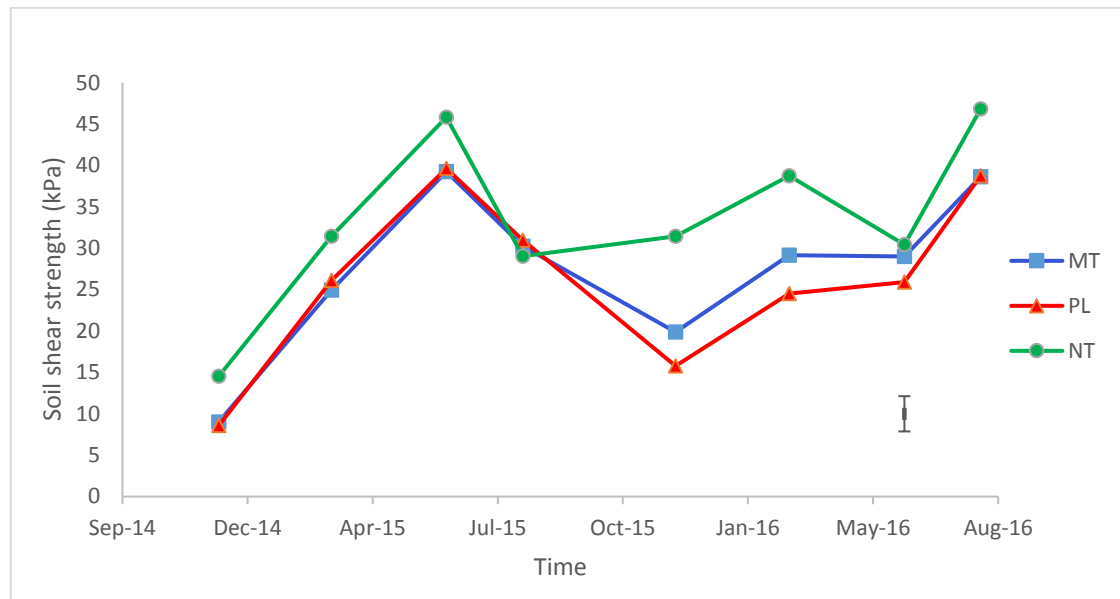


Fig. 2-5. Soil shear strength throughout the growing seasons of wheat and triticale, as influenced by different tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing). Error bars depict S.E.D. (93.01 d.f.) In each year, cultivation practices and harvest were taken place in September and August respectively.

2.3.3.3 Soil Organic Matter (SOM)

Neither tillage system nor residue retention had a significant impact on the organic matter accumulation in the tillage layer 0-30 cm. However, the stratification of the OM was different in the three layers and this was influenced by cultivation. In the 0-5 cm layer, organic matter content was significantly higher in NT and MT compared to PL ($P < 0.05$) (Fig. 2-6 A). In the lower depths (5-15 cm and 15-30 cm), there was no treatment effect on the amount of organic matter (Fig. 2-6 B, C).

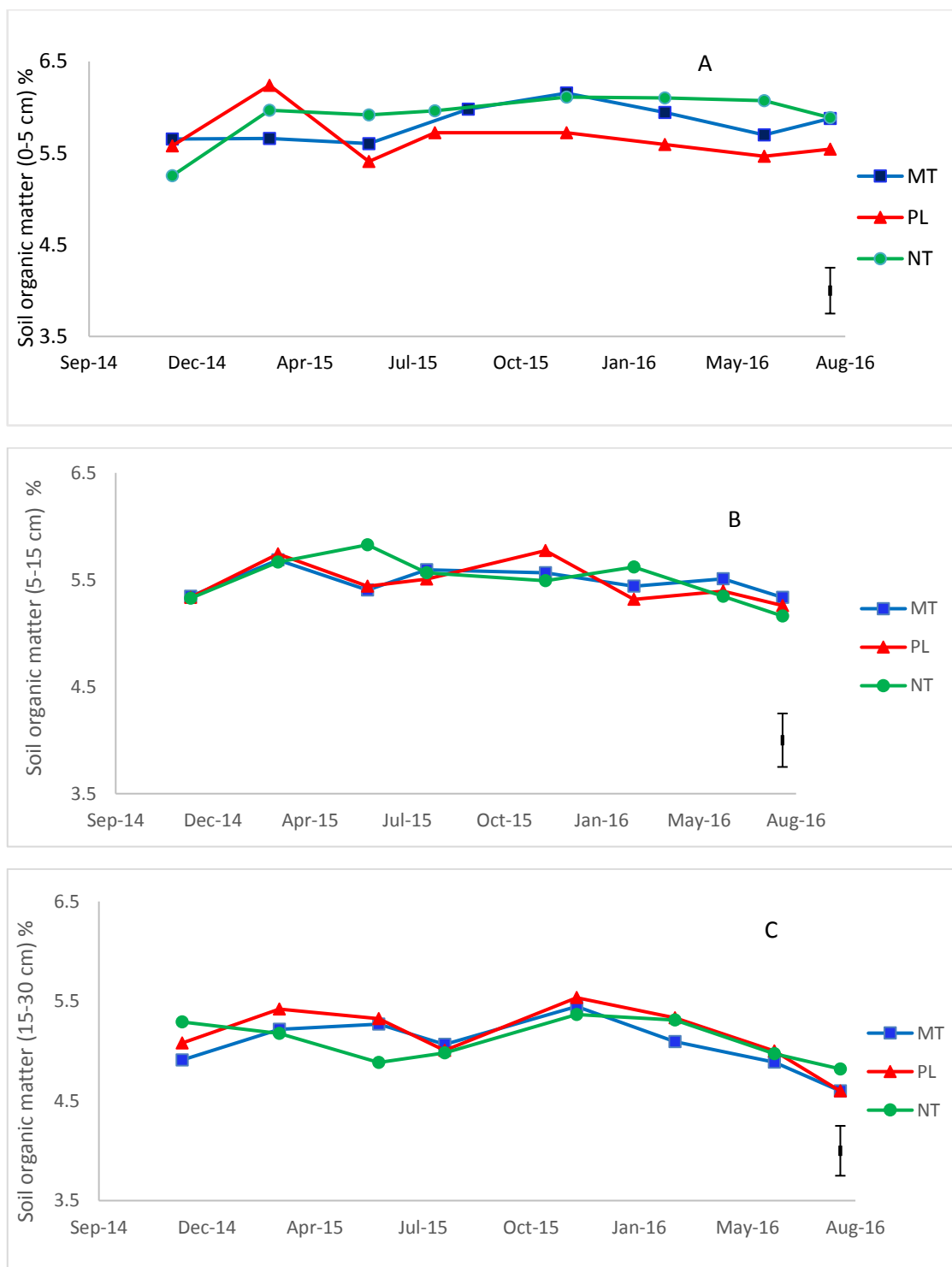


Fig. 2-6. Soil organic matter in the depth A: 0-5 cm, B: 5-15 cm and C: 15-30 cm of the soil surface throughout the growing seasons of wheat and triticale, as influenced by different tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing). Error bars present S.E.D. (123.94 d.f.) In each year, cultivation practices and harvest happened in September and August respectively.

2.3.3.4 Soil moisture content

SMC at 5 cm was affected significantly by cultivation ($P < 0.001$, Fig. 2-7). Averaged across the year, the ploughed treatment had significantly lower soil moisture content (16.2%) than the MT (17.9%) and NT (17.6%) treatments ($P < 0.05$) as presented in (Table 2-3). Retention of the plant residues did not have a significant effect on SMC, although the average was higher when residues were retained at 17.27%, compared to 17.15% when residues were removed.

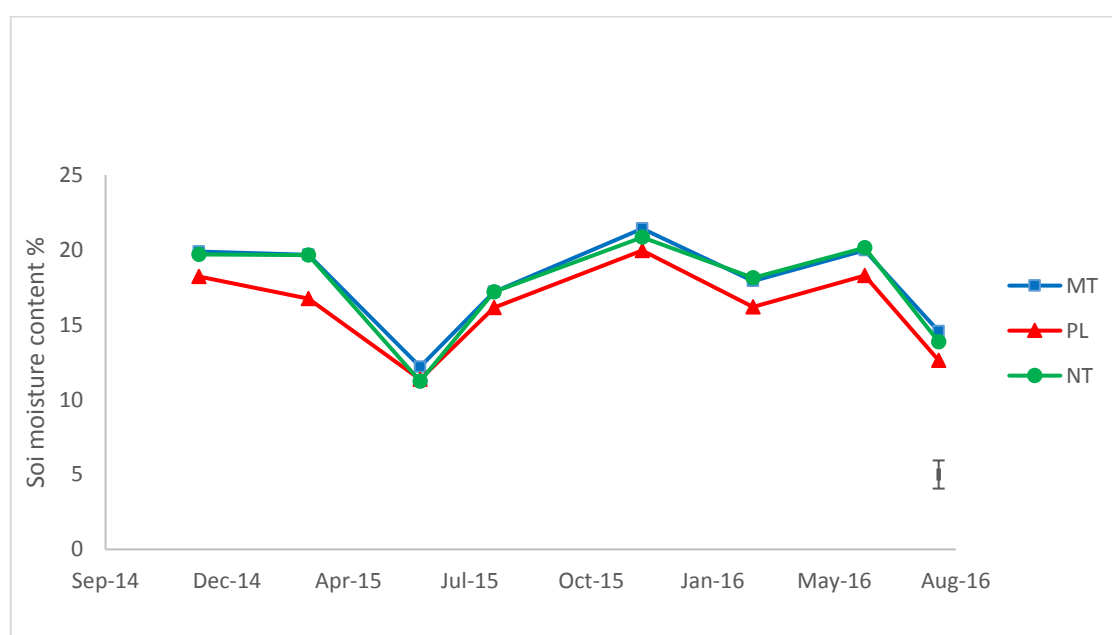


Fig. 2-7. Soil moisture content (0-5 cm) throughout the growing season of wheat and triticale, as influenced by different tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing). Error bar represents S.E.D. (37.81 d.f.) In each year, cultivation practices and harvest happened in September and August respectively.

The soil moisture content in the soil profile was measured in the second year only.

Overall the moisture content averaged in the soil profile (0-30 cm) was not affected by the tillage treatments or the residue retention when the triticale was grown (Fig. 2-8).

The pattern was the same over time.

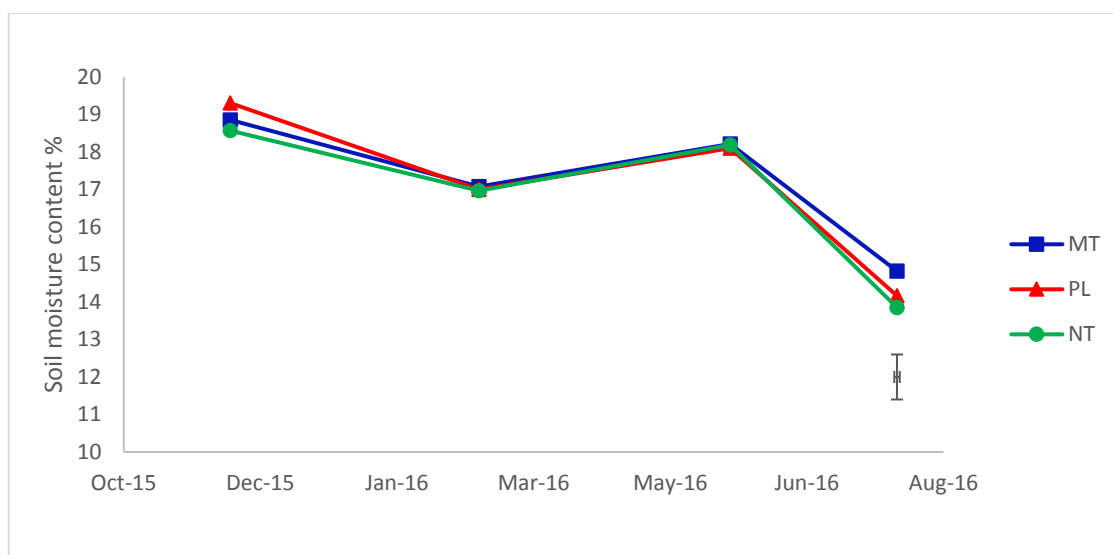


Fig. 2-8 Soil moisture content % averaged in the soil profile 0-30 cm as influenced by the tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing). Error bar represents S.E.D. (22.12 d.f.) In each year, cultivation practices and harvest happened in September and August respectively.

Table 2-3. Soil bulk density, shear strength, water content (%) averaged across the sampling period, as influenced by different tillage systems: no tillage (NT), minimum tillage (MT) and ploughing (PL), and residues retention.

Tillage method	Bulk density (g.cm ⁻³)	Shear strength (kPa)	Soil water content % (0-5 cm)
NT	1.30	34.01	17.59
MT	1.21	27.44	17.86
PL	1.28	25.98	16.19
<i>P</i> value	<0.001	<0.001	<0.001
LSD	0.03	1.74	0.48

2.3.3.5 Penetration resistance *PR*

A. Penetration resistance (0-10 cm)

NT had the greatest *PR* averaged over time, 1.53 MPa, followed by MT at 1.32 MPa and PL which was the lowest at 1.12 MPa ($P < 0.001$). The residues did not have a significant effect on *PR* ($P > 0.05$). During the first year (wheat season), the difference between the *PR* in NT and MT was not significant, but PL was significantly lower than both NT and MT ($P < 0.05$). In the second season, NT continued to have the strongest soil penetration resistance (Fig. 2-9).

The PR changed significantly over time ($P<0.001$) which is likely to be largely impacted by changes in soil moisture. When the experiment started in December 2014, the mean PR was 0.77 MPa, increasing gradually to 1.48 MPa by June 2015, and to a peak of 2.2 MPa in August 2015 over the first 10 cm. In the second year of this study, the trend of the mean PR value was different from the first year. In December 2015, PR was 1.55 MPa, then it decreased to 0.85 MPa in June 2016 and then slightly increased to 1.1 MPa in August 2016.

B. Penetration resistance (10-20 cm)

Cultivation system had a significant impact on PR in the depth between 10-20 cm ($P<0.001$). The mean PR value was highest in the MT at 2.03 MPa, 1.92 MPa in the NT and the lowest in PL at 1.31 MPa (Fig. 2-10). The difference between each one of them was significant ($P<0.05$). PR was not affected by residue retention.

The PR values at this depth changed significantly over time in all treatments. During the first year, PR increased significantly from 1.36 MPa in December 2014 to reach a peak of 2.45 MPa in August 2015. In the second year, PR decreased from 2.38 MPa in December 2015 to 1.03 MPa in June 2016, and then increased to 1.38 MPa in August 2016 ($P<0.05$).

C. Penetration resistance (20-30 cm)

Tillage intensity had a significant impact on the soil penetration resistance at 20-30 cm below the soil surface ($P<0.001$) (Fig. 2-11). As previously observed at 10-20 cm, MT had significantly higher PR (2.76 MPa) than NT (2.62 MPa) and PL (2.13 MPa) ($P<0.001$).

Over time, PR changed significantly ($P<0.001$). The effects of the treatments was not significant for the first two measurements. Thereafter, the PR increased significantly to reach a peak of 4.22 MPa in August 2015. In the second year, the mean PR value was highest in December 2015, before decreasing significantly ($P<0.05$) to 1.38 MPa in June 2016 and then increasing to 1.79 MPa in August 2016.

Table 2-4. Mean penetration resistance values at three depths.

Cultivation	PR (0-10 cm) MPa	PR (10-20 cm) MPa	PR (20-30 cm) MPa
NT	1.53	1.92	2.62
MT	1.32	2.03	2.76
PL	1.12	1.31	2.12
P value (d.f. 12)	<0.001	<0.001	<0.001
LSD	0.06	0.1	0.12

D. Penetration resistance at measurement time as influenced by tillage practice, residue retention and depth.

Overall, ploughed treatment always had lower PR in upper layer which then increased at ploughing depth (25 cm). At all measuring times, the penetration resistance (PR) increased with increasing soil depth. In December 2014, PR was affected significantly ($P<0.001$) by both tillage and depth. PR was significantly greater in NT and MT (1.59 MPa) than in PL (1.00 MPa) (Fig. 2-12, A). In June and August 2015, neither the residues nor the tillage systems alone had a significant impact on the PR (Fig. 2-12, B, C). In the second year of the field experiment, PR was significantly different at three measuring times. The observed PR measured in December 2015, PR was highest in NT at 2.62 MPa, 2.5 MPa in MT and 1.57 MPa in the PL ($P<0.001$) (Fig. 2-12, D). In June 2016, PR was affected significantly by tillage ($P<0.05$), as shown in (Fig. 2-12 E). The greatest PR values were detected in MT plots (1.14 MPa) followed by NT (1.12 MPa) with the least values observed in PL plots 0.92 MPa ($P<0.001$). Finally, in August 2016 Fig. 2-12 F shows that

PR was affected significantly by the tillage system ($P<0.05$). PR in NT was greater than in MT and PL (1.59 MPa, 1.49 MPa, 1.25 MPa) respectively. The difference between NT and MT was not significant. The difference between PL and both of NT and MT was significant.

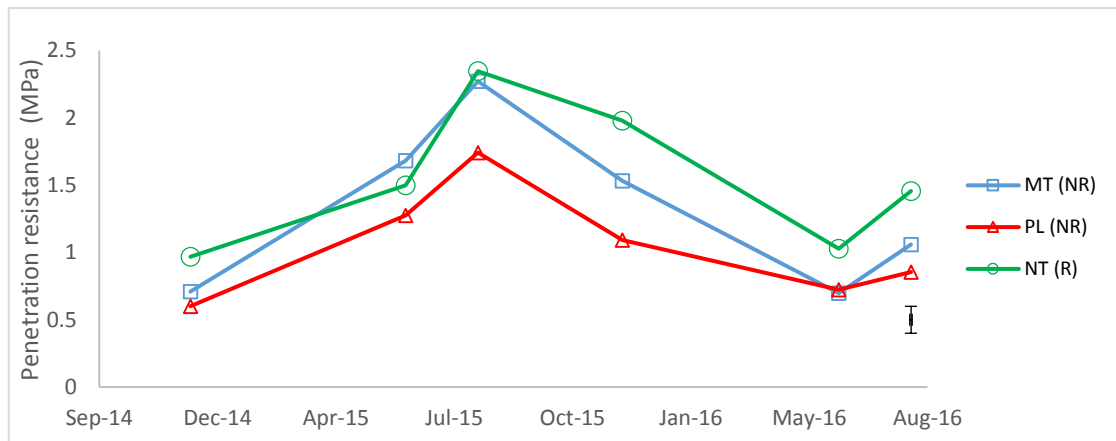


Fig. 2-9. Soil penetration resistance in the top 10 cm of the soil surface throughout the growing seasons of wheat and triticale, as influenced by different tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing). Error bar represents S.E.D. (66.53 d.f.) Each year, cultivation practices and harvest happened in September and August respectively.

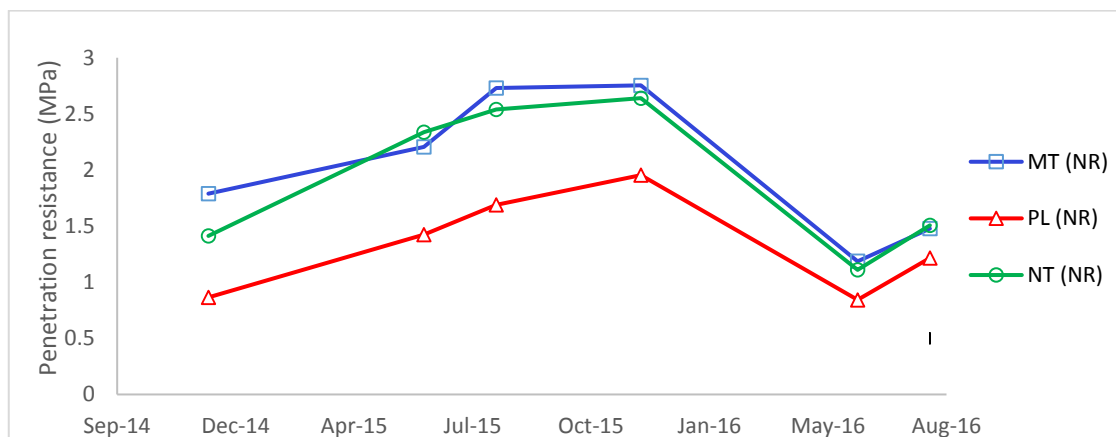


Fig. 2-10. Soil penetration resistance in the depth between 10-20 cm of the soil surface throughout the growing seasons of wheat and triticale, as influenced by different tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing). Error bar represents S.E.D. (57.63 d.f.) In each year, cultivation practices and harvest happened in September and August respectively.

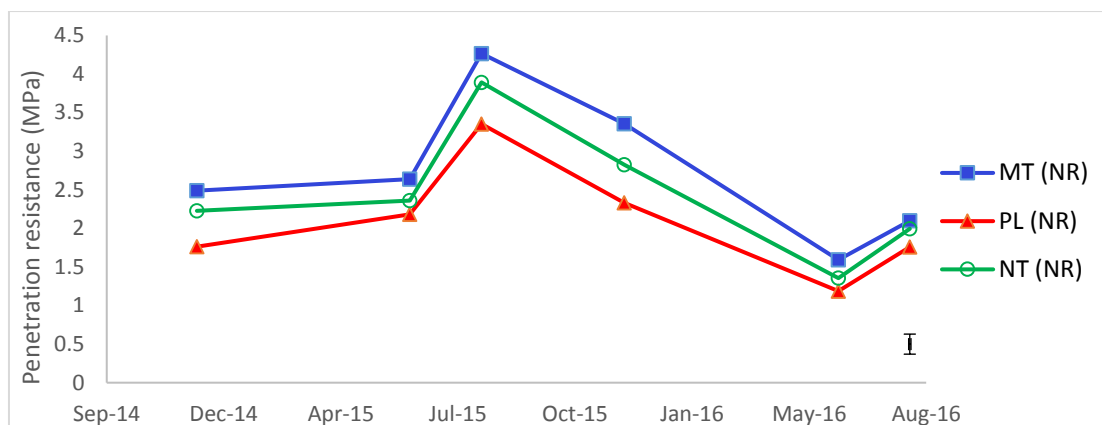


Fig. 2-11. Soil penetration resistance in the depth between 20-30 cm of the soil surface throughout the growing seasons of wheat and triticale, as influenced by different tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing). Error bars present S.E.D. (70.45 d.f.) Each year, cultivation practices and harvest were taken place in September and August respectively.

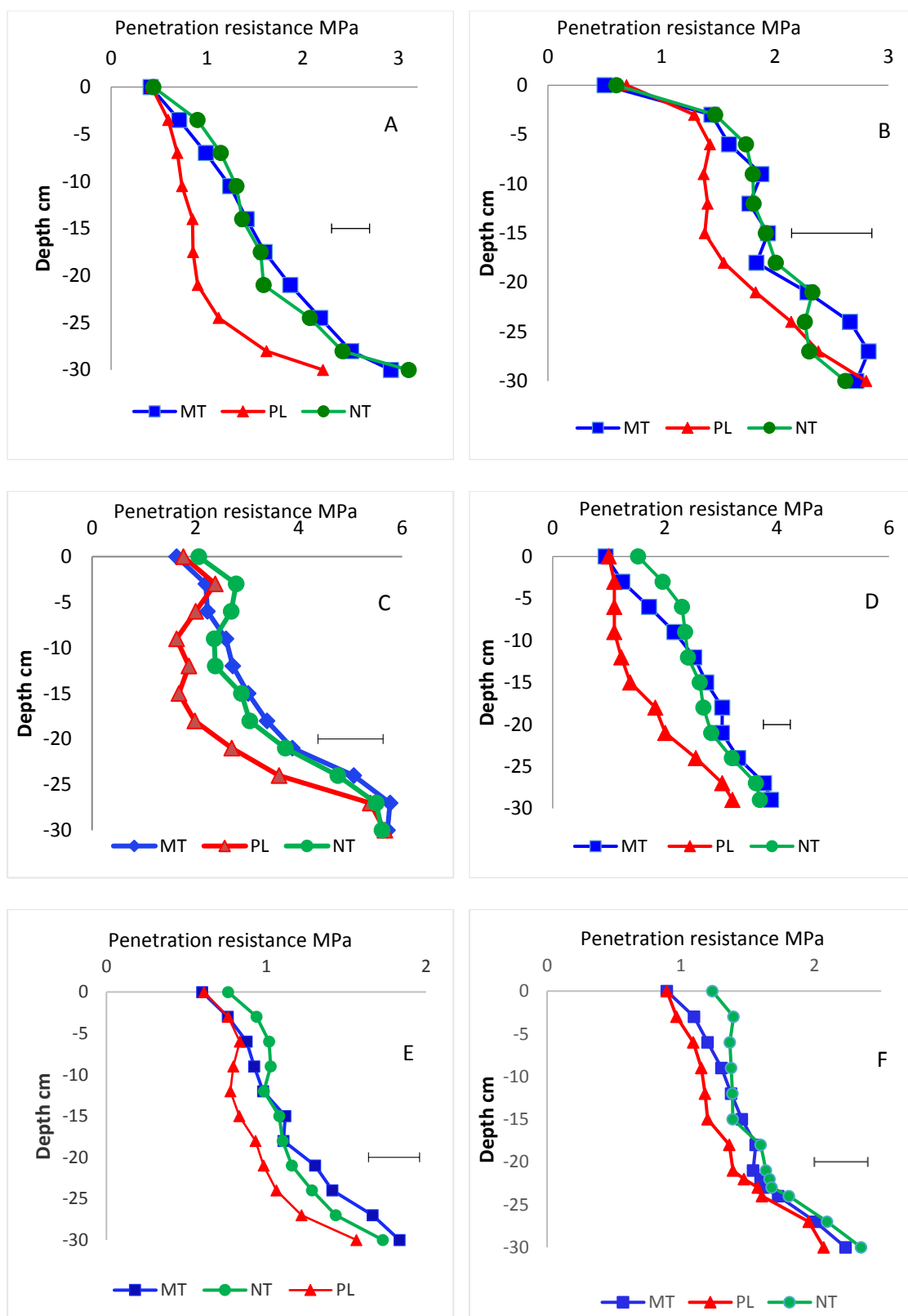


Fig. 2-12. Average penetration resistance during the growing seasons of winter wheat and triticale, as influenced by three different tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing). A, B, C, D, E, F: penetration resistance in December 2014, June, August, and December 2015, June and August 2016 respectively. Error bars depict S.E.D. Cultivation practices and harvest took place in September and August respectively.

2.3.3.6 *Soil structure in both years*

A. *Micromorphology assessment*

Before carrying out the imaging assessment of the core soil samples, a micromorphological assessment was undertaken to investigate the effects of the different tillage practices and the retention of plant residues on soil structure. This assessment showed that the soil structure varied considerably between the treatments. [Fig. 2-13](#) shows few example images of the different treatments.

NT soil samples tended to have less porosity during the early stages, but this increased clearly over time. Overall, compared to PL and MT soils, NT had fewer large-sized pores. The pores in NT were more elongated, rounded and vertically oriented than other tillage treatments. This could be attributed to the movement of the earthworms to get the residues down inside the soil. This seems to be one of the ways through which plant residues are incorporated in the soil when NT is undertaken. The incorporation of the residues increased over time. Residues were not well incorporated in samples which were collected in December 2014. Thereafter, the differences between plots covered with residues or not, diminished as elongated and circular pores started to appear in all samples.

Soil structure under MT looked different from NT. The soil under this treatment was more fragmented. Horizontal cracks separating soil aggregates were easily seen. These cracks might be a result of the mechanical disturbance of the soil caused by discs and tines during the soil preparation process. Bio-pores caused by the earthworms were less noticeable in MT plots. The residues were well distributed along the top 10 cm of the

soil surface during the whole course of the experiment. No clear differences were noticed in the amount of plant residues retained between all treatments.

In the ploughed soil, the aggregates were smaller than in the other types of tillage. The plant residues were observed along the whole depth of the samples and there was less aggregation. This could be because of the deep tillage and the rolling and pressing process which followed the plough. In the early stages of the experiment, these samples looked more disturbed compared to other tillage treatments with varied-size cracks. No bio-pores were observed. In the later stages, large pores were recorded compared to other tillage practices. The incorporated residues were most likely to fill the spaces between soil aggregates.

Overall, soil structure changed over time. As soil temperature and moisture content was different and this could have impacted the aggregation and the plant residue decomposition. Soil samples which were collected in summer had more cracks than those collected in wet times of the year. On untilled soils, SOM notably accumulated in the upper part of the soil.

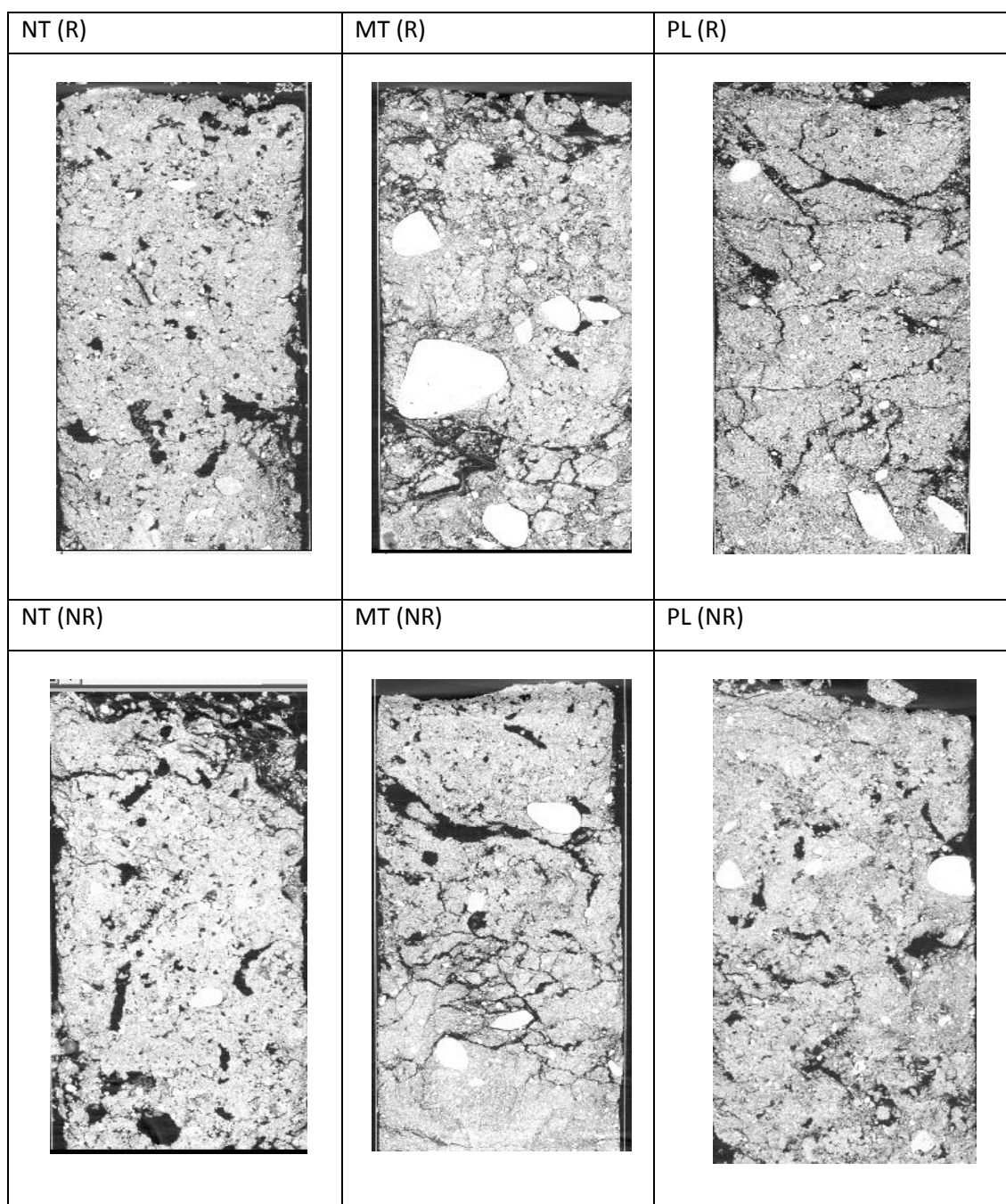


Fig. 2-13. CT scan images showing the effects of the different treatments on the soil structure morphology. NT (R) no tillage with residues. NT (NR) no tillage without residues. MT (R) minimum tillage with residues. MT (NR) minimum tillage without residues. PL (R) ploughing with residues. PL (NR) ploughing without residues.

B. Soil porosity %

No significant effects of residue retention or cultivation regime on the soil porosity were observed. On average, the porosity was 20.1% in MT, 19.3% in PL and 17.9% in NT. Soil porosity was affected significantly by time ($P<0.001$). This could be attributed to the low porosity percentage $\sim 14\%$ during the first two measurements in December 2014 and March 2015, and then the significant increase to more than 21% for the rest of the experiment (Fig. 2-14).

On average, the highest porosity value was noted in June 2015, this could be due to dry soil at that time with a significant difference from the two measurements before in December 2014 (porosity 14.74%) and March 2015 (porosity was 14.33%) ($P<0.05$). At the end of each season, porosity was similar, around 21% in both of August 2015 and 2016.

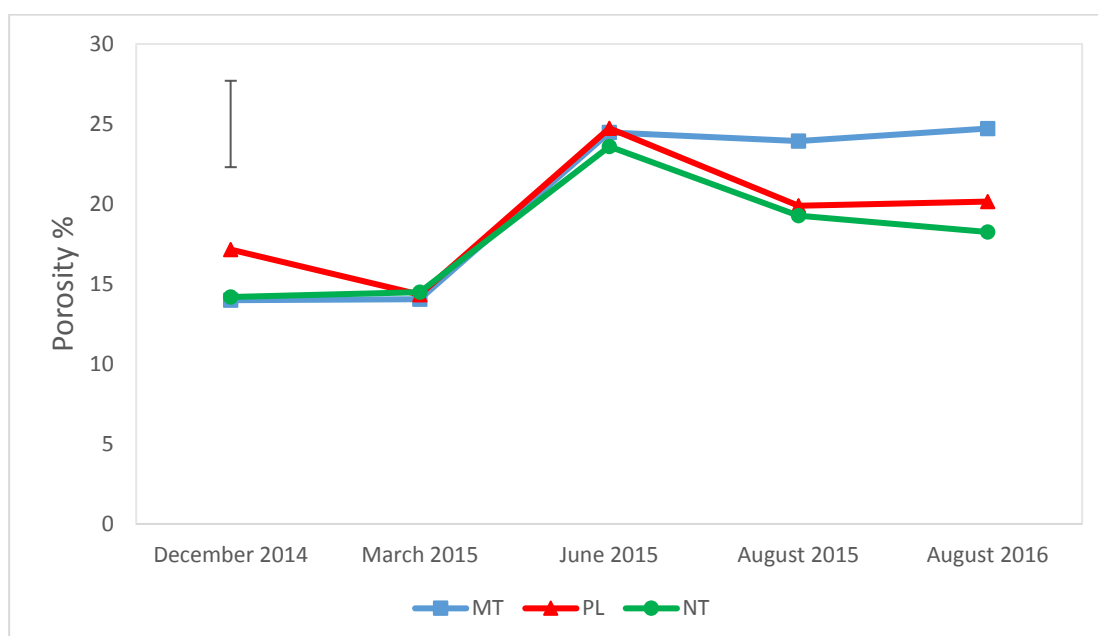


Fig. 2-14. Average soil porosity (%) as influenced by different cultivation practices: no tillage (NT), minimum tillage (MT) and ploughing (PL) over the growing season of wheat and triticale. S.E.D. In each year, cultivation practices and harvest were taken place in September and August respectively.

C. Pore size distribution (PSDcu)

In addition to a significant time effect, both the cultivation system ($P<0.001$) and residue retention ($P<0.05$) had a significant influence on PSDcu (Fig. 2-15). The PSDcu was highest in PL at 76.1 and lower in MT 56.8 and NT 44.8 respectively. The mean PSDcu was 63.5 residues were retained while it was 55 when residues were removed.

PSDcu changed significantly over time ($P<0.05$). The highest value was (73.4) and it was recorded in August 2016 just before the triticale harvest, whereas it was the lowest (44.8) in March 2015. In the first year, PSDcu changed differently depending on the cultivation strategies. In the PL, PSDcu increased from 62.1 in December 2014 to 74.2 in August 2015. Under NT, PSDcu increased from 29.4 to 54.1 and from 36.4 to 69.5 under MT in the same time. By the end of the second year, PSDcu was 85, 69.7 and 65.4 in PL, MT and NT respectively.

Comparing between the observed PSDcu at the start of the experiment and at the end, the results show that PSDcu at the end of the experiment had doubled in the NT plots (122%) and to slightly less in the MT plots at approximately 91%, in PL plot the value had not changed. The largest amount of large pores were detected at the end of the experiment in August 2016.

Fig. 2-16 shows graphs for the effects of residues and the different tillage systems on the PSDcu in August 2015. Residue retention increased PSDcu ($P<0.05$) which increased with the increase in the tillage intensity ($P<0.001$). It can be seen in this graph, that the pore size ranged from 0.3 mm^2 ($\log_{10} [-0.5]$) to 0.4 mm^2 ($\log_{10} [2.5]$). The influence of the residue is clear in all treatments as the efficient is higher when the residues were

retained. The influence of the cultivation is also clear. Pores with more than 2 and 2.5 mm² increased in PL, MT and NT respectively.

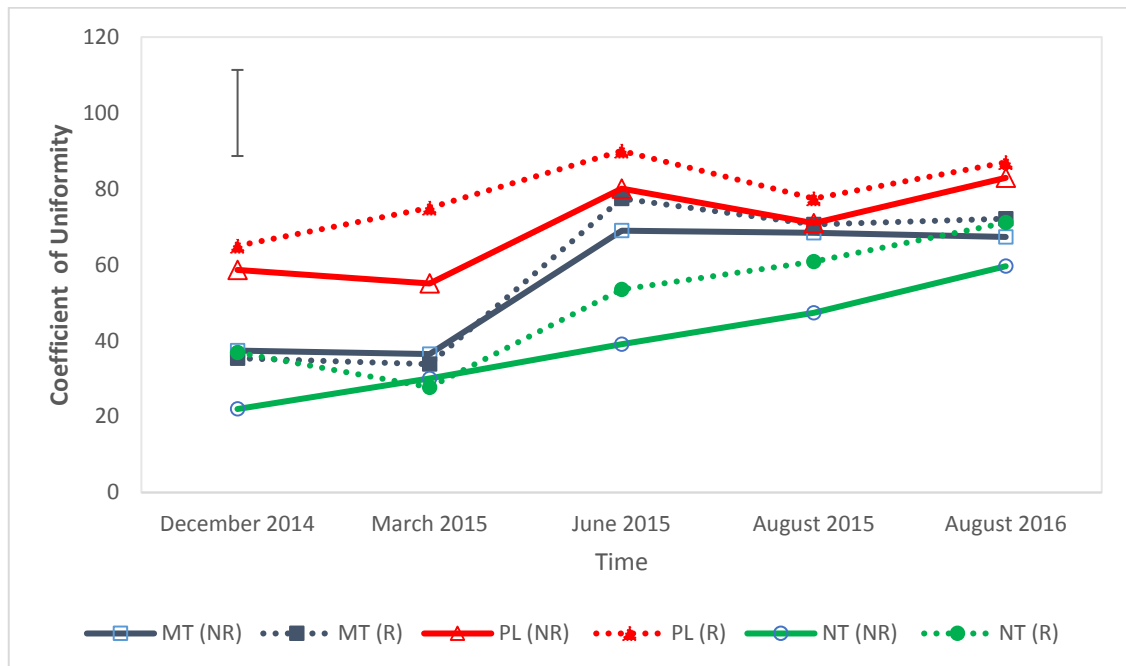


Fig. 2-15. Pore size distribution, Coefficient of Uniformity (PSDcu) throughout the growing seasons of wheat and triticale, as influenced by different tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing) and plant residue retention (R: residues retained, NR: residues removed). Error bars depict S.E.D. In each year, cultivation practices and harvest happened in September and August respectively.

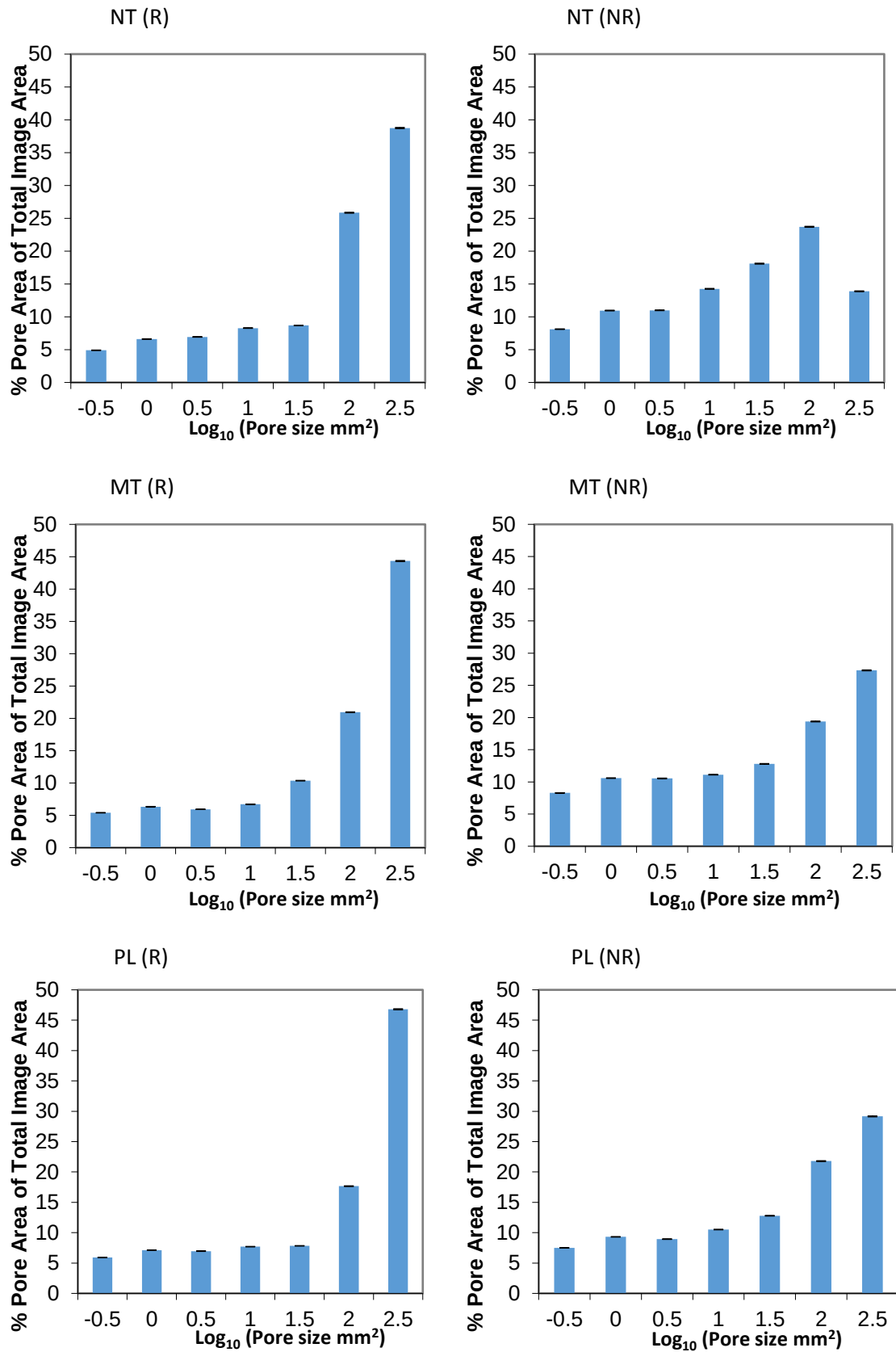


Fig. 2-16. Pore size distribution in August 2015. NT (R): No tillage and residues retained. NT (NR) no tillage, residues removed, MT (R) minimum tillage and residues retained, MT (NR) minimum tillage and residues removed. PL (R) ploughing and residues retained, PL (NR) ploughing and residues removed. Error bars represent SEM.

D. Average pore size

Residue retention increased the average pore size ($P<0.05$) from 0.37 mm² to 0.45 mm².

Fig. 2-17 outlines the differences in the average pore size at each measuring point as influenced by residue retention. Fig. 2-18 presents binary images depicting the impact of the residue retention on soil pore size. An increase in larger soil pores can be seen in March, June and August 2015 when residues were retained.

The effect of the residue retention was significant in March, June and August 2015 but not significant in December 2014 and August 2016. Time was not a significant factor influencing the pore size and there was no effect of cultivation.

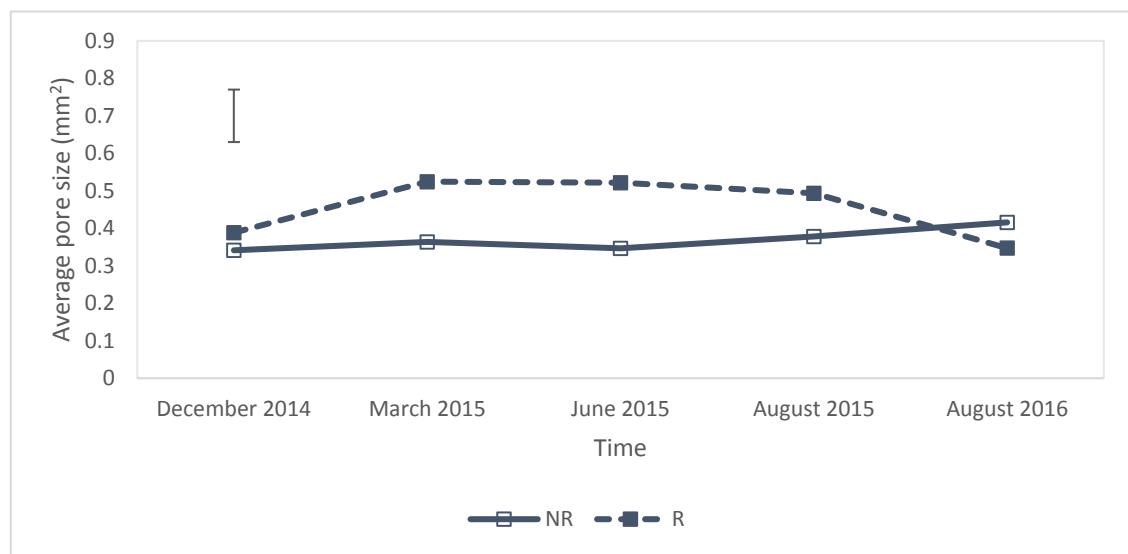


Fig. 2-17. Average pore size as influenced by the residue retention over the growing season of wheat and triticale. R: residues retained and NR: residues removed. Error bars represent S.E.D. In each year, cultivation practices and harvest happened in September and August respectively.

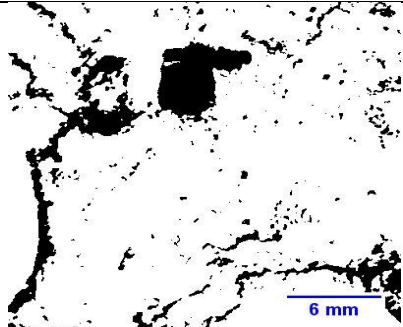
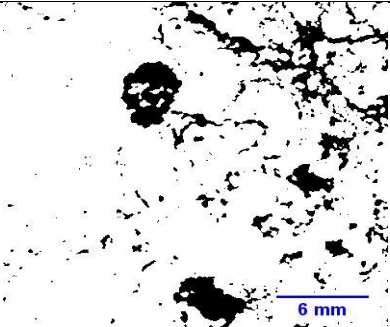
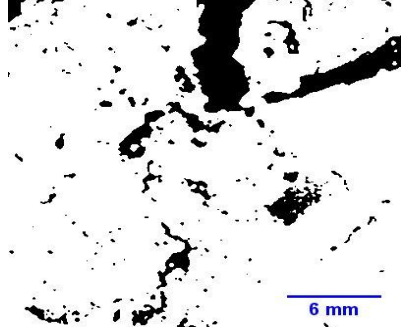
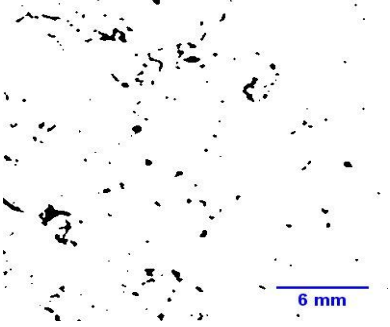
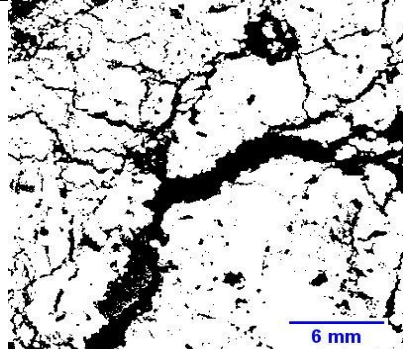
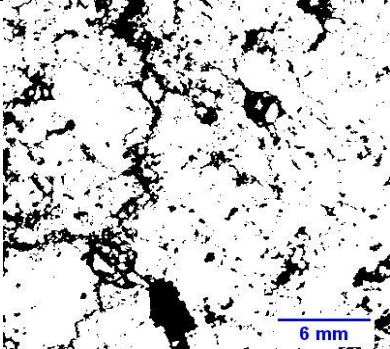
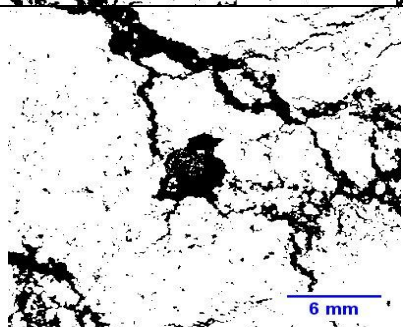
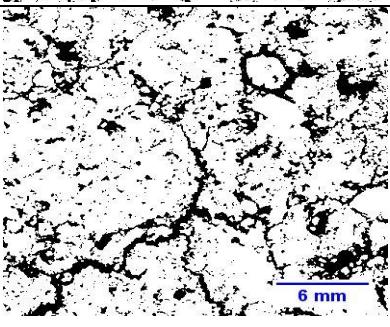
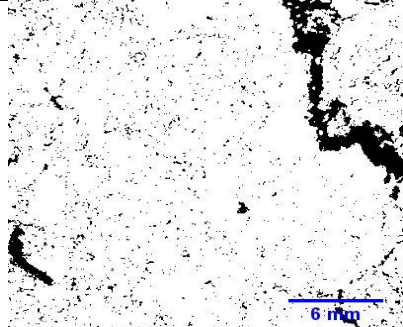
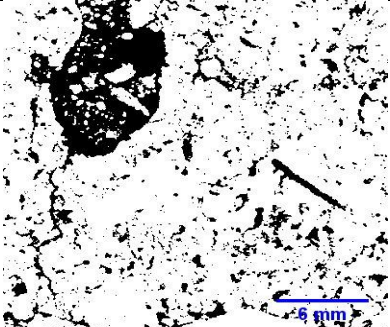
Date	Residues retained	Residues removed
December 2014		
March 2015		
June 2015		
August 2015		
August 2016		

Fig. 2-18. Binary images showing the changes in the pore sizes as influenced by residue retention. Black colour refers to pore spaces.

E. Pore connectivity

Pore connectivity was not affected by tillage or the residues individually (Fig. 2-19). However, pore connectivity ratio was 92.11% in MT, 91.07% in NT and 89.52% in PL. As the images show in Fig. 2-20 pore connectivity changed significantly over time ($P<0.001$). It was significantly higher ($P<0.05$) in June 2015 (94.83%) and August 2015 (93.62%) compared to December 2014 (89.04%), March 2015 (87.9%) and August 2016 (89.1%). The interaction between cultivation, residue retention and time was significant ($P<0.001$). During the first year, pore connectivity increased in all treatments. In the second year the increase continued in the NT and MT, but it decreased in the PL. Overall, by the end of the experiment, an increase in pore connectivity percentage was noted in both of NT and MT estimated by 5.78% and 4.42% respectively, whereas a 9.67% decrease in the connectivity was noticed in the PL.

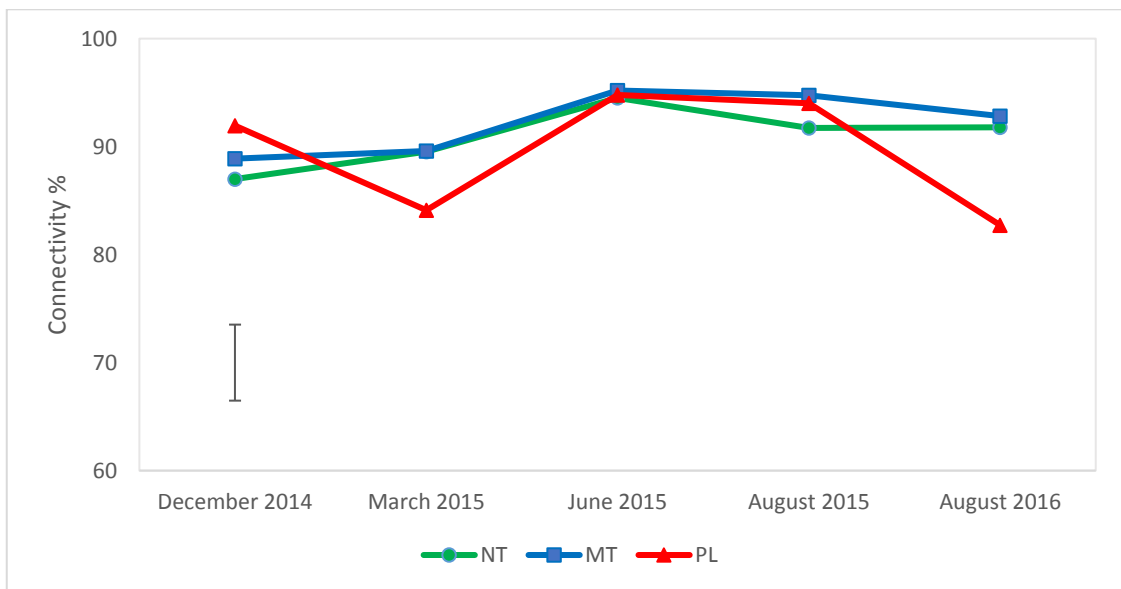


Fig. 2-19. Pore connectivity as influenced by different tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing) over the growing season of wheat and triticale. Error bars represents S.E.D. In each year, cultivation practices and harvest happened in September and August respectively.

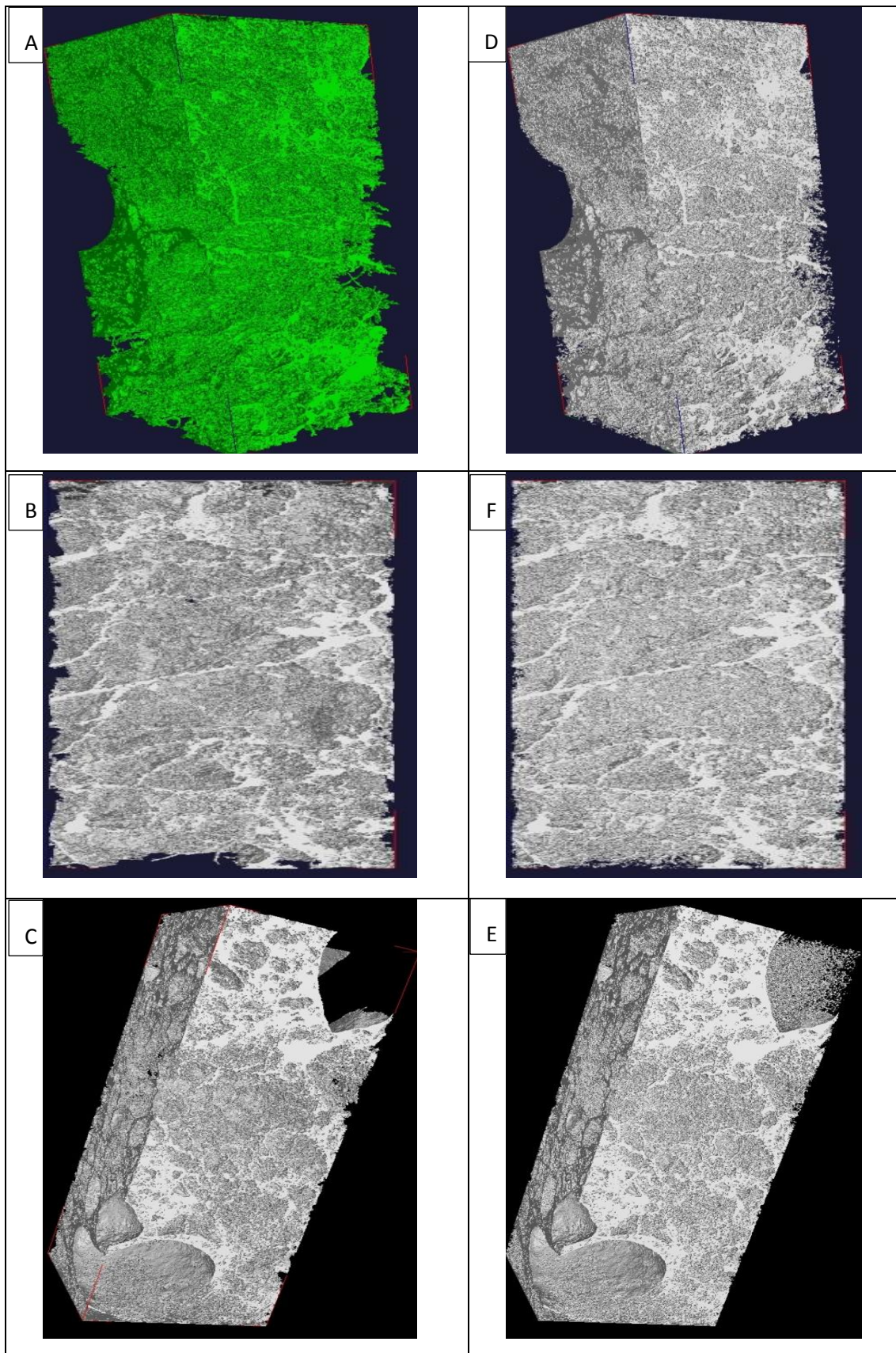


Fig. 2-20. CT scan images comparing the pore connectivity in the different tillage treatments. These images are for samples collected in September 2015. A: Connected soil pores, NT (NR), B: Connected soil pores, MT (NR), C: Connected soil pores, PL (R), D: All soil pores, NT (NR), E: All soil pores, MT (NR), F: All soil pores PL (R).

2.3.4 Crop measurements

2.3.4.1 Wheat plant population

The highest plant population was observed in NT plots 265.4 plant.m⁻², 256.7 plant.m⁻² in the MT plots and the lowest 226.2 plant m⁻² in the PL plots ($P<0.05$). The difference between the plant count in the MT and NT was not significant (Fig. 2-21). Residue retention did not have an impact on the plant population.

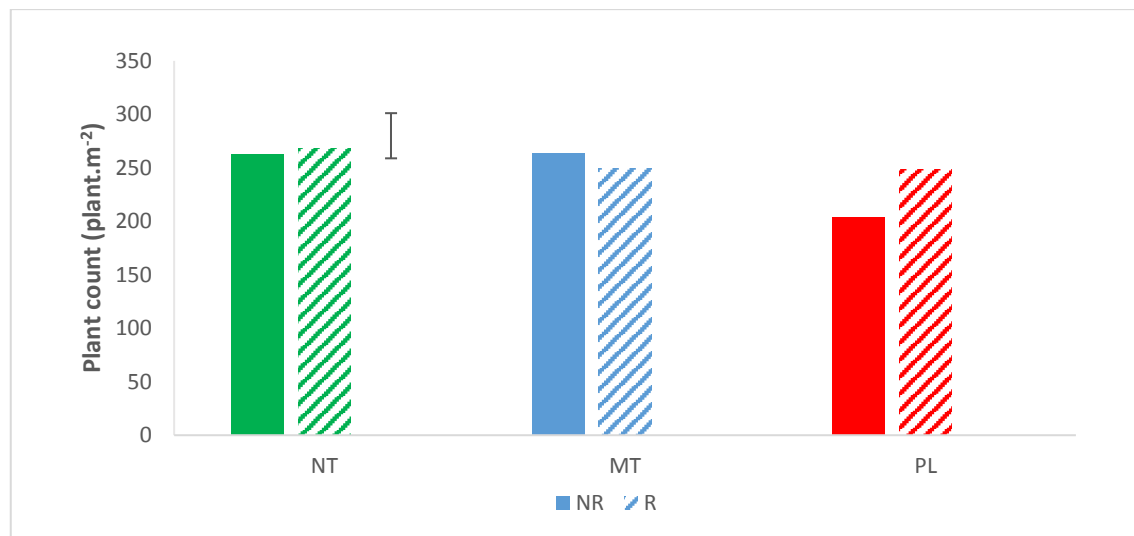


Fig. 2-21. Wheat plant population as affected by tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing) and residues retention (R: residues retained, NR: residues removed). Error bars depict S.E.D. (9.26 d.f.).

2.3.4.2 Wheat Normalised Differences Vegetation Index NDVI

Measuring the NDVI started on 15 April 2015 and continued every 2 weeks until the 15 July 2015. Neither the residues nor the cultivation systems had an effect on the NDVI values. However, NDVI values changed significantly over time ($P<0.001$). NDVI values increased steadily from 0.71 on 15 April 2015 to reach a peak at 0.8 on 01 June 2015. The lowest recorded measurement was 0.55 on 15 June 2015 (Fig. 2-22).



Fig. 2-22. Changes in Normalised differences in vegetation index during the growing season of wheat as affected by tillage systems (NT: no tillage, MT: minimum tillage, PL: ploughing) and residue retention (R: residues retained, NR: residues removed). Error bar depicts standard error of differences SED. Cultivation practices took place in September and crop was harvested in August.

2.3.4.3 Wheat yield

At the end of the first year of the experiment, wheat grain yield was not significantly affected by the cultivation system or the residue retention. The highest grain yield 11 t.ha⁻¹ was observed in the PL plots, whereas it was 10.74 t.ha⁻¹ and 10.64 t.ha⁻¹ in MT and NT respectively. Residue retention had no significant effect on yield. Fig. 2-23 outlines the differences in the grain yield as influenced by the different treatments. As there were no significant effects of cultivation or residues on wheat yield, the relationships with soil physical properties were not explored.

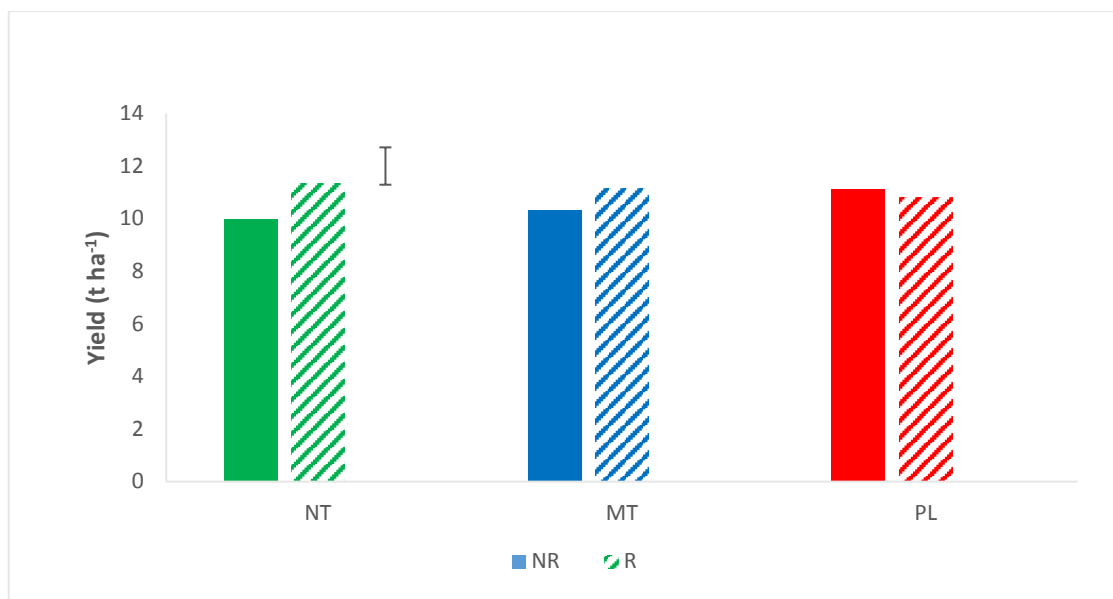


Fig. 2-23. Wheat yield as affected by tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing) and residues retention (R: residues retained, NR: residues removed). Error bar depicts S.E.D. (11.43 d.f.)

2.3.4.4 *Triticale plant population*

Greater plant population was recorded under MT at 193.1 plant m⁻² and PL at 192.1 plant m⁻² compared to NT (149 plant m⁻²) ($P < 0.05$) as shown in Fig. 2-24. The residues did not have a significant effect on the plant count. The correlation matrix between the plant number and soil physical properties showed that plant population negatively correlated with soil bulk density and shear strength, but positively with soil organic matter in the depth 15-30 cm (Table 2-5).

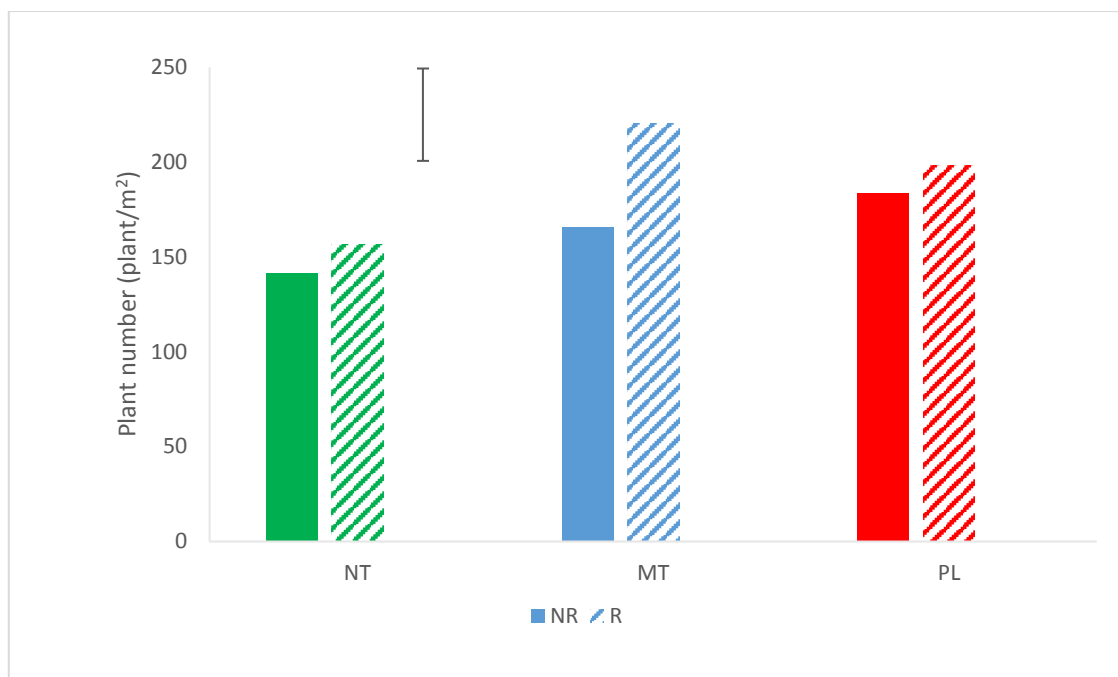


Fig. 2-24 Triticale plant count as affected by tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing) and residues retention (R: residues retained, NR: residues removed). Error bar depicts SED. (9.18 d.f.)

2.3.4.5 Triticale normalised difference vegetation index NDVI

The NDVI was measured 5 times during the triticale crop, starting at stage 39 when the flag leaf ligule became just visible. The measurements were continued for the subsequent two months. The NDVI was not affected by either the tillage regimes or the residues retention, but it changed significantly over time ($P < 0.001$) (Fig. 2-25). The measurement was taken for the first time on 23 May 2016, the NDVI was 75.14, thereafter its values decreased significantly in the subsequent measurements until the last one on 25 July 2016.

Table 2-5. Correlation matrix between the soil physical properties and the plant count during the plant triticales crop establishment in December 2015.

Soil organic matter (0-5 cm)	1											
Soil organic matter (5-15 cm)	-0.08	1										
Soil organic matter (15-30 cm)	0.16	0.07	1									
Soil shear strength	0.38	-0.34	-0.08	1								
Soil penetration resistance (0-10 cm)	0.43	-0.55	-0.21	0.77	1							
Soil penetration resistance (10-20 cm)	0.30	-0.58	-0.38	0.41	0.71	1						
Soil penetration resistance (20-30 cm)	0.63	-0.32	-0.25	0.36	0.63	0.80	1					
Soil bulk density	0.23	-0.28	-0.09	0.19	0.23	-0.01	-0.14	1				
Soil moisture content % in the soil profile	0.35	0.35	0.32	-0.19	-0.36	-0.32	-0.22	0.12	1			
Soil moisture content (0-5 cm) %	-0.16	-0.04	-0.13	-0.3	-0.27	-0.22	-0.37	0.53	0.1	1		
Plant population (plant m ⁻²)	-0.21	-0.13	0.5*	-0.35*	-0.28	-0.1	-0.02	-0.38*	-0.24	-0.19	1	
Combine yield t ha ⁻¹	-0.27	-0.09	-0.11	-0.57	-0.42	-0.06	-0.1	-0.19	-0.01	-0.12	0.28	1
	Soil organic matter (0-5 cm)	Soil organic matter (5-15 cm)	Soil organic matter (15-30 cm)	Soil shear strength	Soil penetration resistance (0-10 cm)	Soil penetration resistance (10-20 cm)	Soil penetration resistance (20-30 cm)	Soil bulk density	Soil moisture content % in the soil profile	Soil moisture content % (0-5 cm)	Plant population (plant/m ²)	Combine yield t/ha

The critical value is 0.33 (n=24, $P<0.1$). (*) refers to significant correlations.

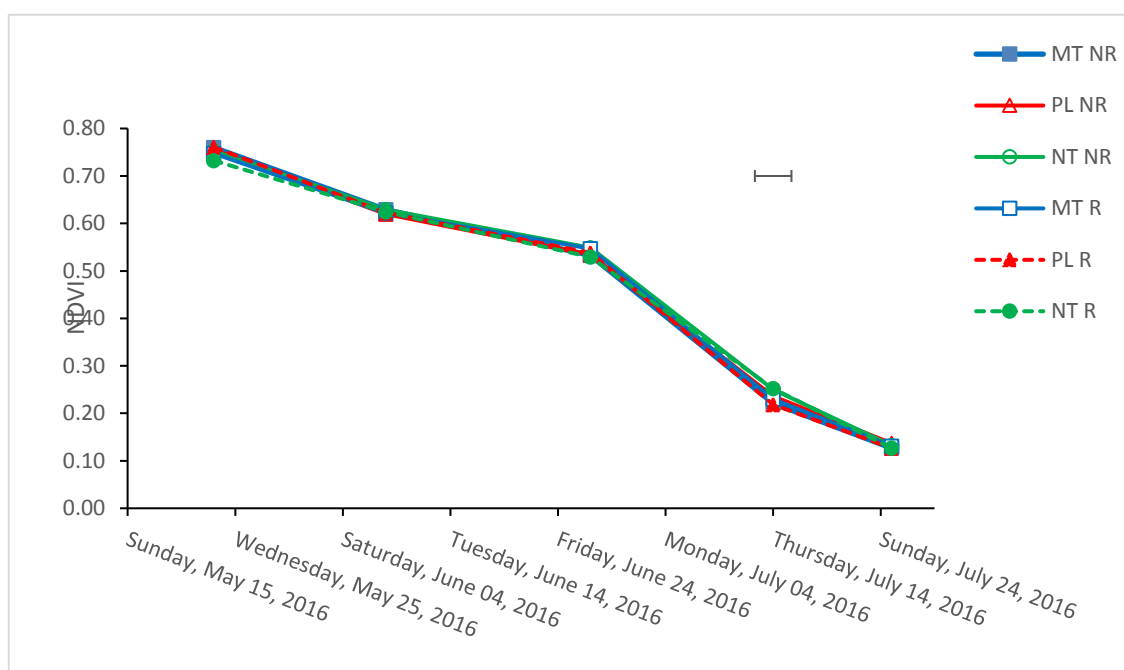


Fig. 2-25. Changes in Normalised Differences in Vegetation Index during the growing season of triticale as influenced by different tillage systems: no tillage (NT), minimum tillage (MT) and ploughing (PL), and residues retention. Error bar depicts S.E.D. (24.96 d.f.). Cultivation practices were taken place in September 2015 and crop was harvested in August 2016.

2.3.4.6 Triticale grain yield

The grain yield was affected significantly by the cultivation system ($P < 0.05$, Fig. 2-26).

The highest yield was observed in PL and MT where it was 6.97 and 6.92 t ha^{-1} respectively, but it was significantly less under the NT at 6.27 t ha^{-1} . The yield was not affected whether the previous crop residues were retained or removed.

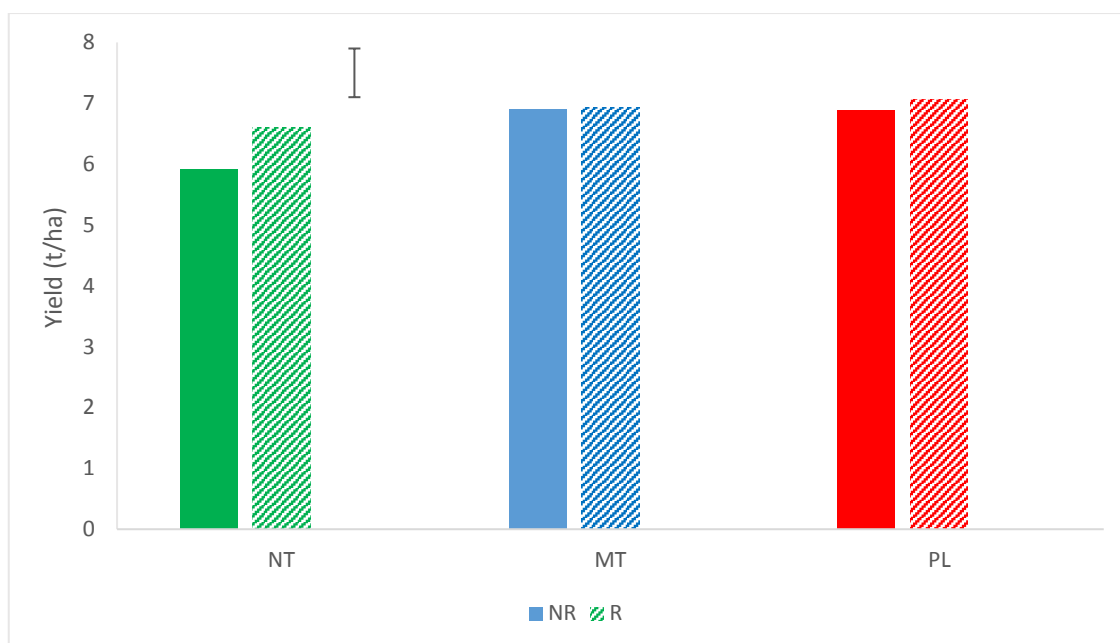


Fig. 2-26. Triticale grain yield as influenced by tillage practices (NT: no tillage, MT: minimum tillage, PL: ploughing) and residues retention (R: residues retained, NR: residues removed). Error bars depict S.E.D. (13.32 d.f.).

The triticale yield was correlated with eight factors: shear strength in December 2015, penetration resistance (0-10 cm) in December 2015, penetration resistance (0- 10 cm) in August 2016, bulk density in June 2016, average pore number in August 2016, pore area in August 2016, soil moisture content (%) in June 2016, and soil moisture content (%) in August 2016 (Table 2-6). Inputting these factors in a Generalised Regression Model and dropping the insignificant factors consecutively showed that triticale yield was best predicted by two factors; soil moisture % (August 2016) and soil shear strength (December 2015) as the regression analysis was highly significant ($P < 0.001$) and accounting for 43.1 % of the variation (Table 2-7, Equation 2). This may mean that the factors with are not shown in the equation have been masked by factors which are shown.

Grain yield = 3.55 + 0.29 soil moisture content (%) in August 2016 - 0.04 shear strength in December 2015 (Equation 2)

The lower moisture content in August in the NT compared to PL and MT might account for yield reduction under NT. In August, the soil water content was significantly higher in MT compared to both of NT and PL. The equation shows also that the increase in the soil shear strength in December 2015 affected the yield production significantly.

Table 2-6. The correlation matrix between triticale yield ad soil physical properties during the triticale growing season.

Shear strength (Dec 2015)	1																	
Shear strength (March 2016)	0.68	1																
Shear strength (June 2016)	0.48	0.35	1															
Shear strength (August 2016)	0.59	0.53	0.27	1														
Penetration resistance (0-10 cm) (December 2015)	0.77	0.65	0.58	0.51	1													
Penetration resistance (0-10 cm) (June 2016)	0.64	0.44	0.39	0.48	0.60	1												
Penetration resistance (0-10 cm) (August 2016)	0.81	0.74	0.49	0.51	0.68	0.49	1											
Penetration resistance (10-20 cm) December 2015	0.41	0.51	0.40	0.39	0.73	0.26	0.28	1										
Penetration resistance (10-20 cm) (June 2016)	0.22	0.41	0.28	0.19	0.62	0.21	0.12	0.80	1									
Penetration resistance (10-20 cm) (August 2016)	0.42	0.42	0.46	0.29	0.72	0.28	0.17	0.89	0.74	1								
Penetration resistance (20-30 cm) December 2015	0.36	0.45	0.38	0.21	0.63	0.11	0.30	0.80	0.81	0.78	1							
Penetration resistance (20-30 cm) (June 2016)	-0.07	0.13	0.10	0.10	0.41	0.08	-0.12	0.74	0.82	0.71	0.70	1						
Penetration resistance (20-30 cm) (August 2016)	0.43	0.57	0.34	0.48	0.49	0.23	0.43	0.38	0.17	0.44	0.32	0.12	1					
Bulk density (December 2015)	0.18	0.08	0.43	0.06	0.23	0.09	0.33	-0.01	-0.20	0.00	-0.14	-0.24	0.39	1				
Bulk density (March 2016)	0.29	0.08	0.10	0.31	0.18	0.37	0.30	-0.28	-0.29	-0.27	-0.41	-0.37	0.17	0.27	1			
Bulk density (June 2016)	0.37	0.18	0.30	0.02	0.44	0.36	0.28	0.28	0.08	0.26	0.02	0.04	0.23	0.32	0.41	1		
Bulk density (August 2016)	0.35	0.16	-0.01	0.31	0.05	0.41	0.31	-0.17	-0.37	-0.20	-0.37	-0.39	0.00	0.23	0.48	0.50	1	
Pore number (August 2016)	-0.39	-0.37	-0.39	0.01	-0.38	-0.47	-0.35	0.10	0.04	-0.08	0.13	0.23	-0.20	-0.40	-0.34	-0.44	-0.26	1
Pore Area (August 2016)	-0.28	-0.19	-0.25	0.10	-0.14	-0.25	-0.39	0.35	0.20	0.29	0.25	0.34	-0.06	-0.19	-0.25	-0.30	-0.12	0.53
Pore Size (August 2016)	-0.01	-0.08	0.03	0.11	0.09	-0.06	-0.22	0.25	0.12	0.41	0.15	0.15	0.05	0.02	0.18	0.14	0.02	0.05
Porosity % (August 2016)	-0.25	-0.18	-0.28	-0.05	-0.10	-0.24	-0.38	0.40	0.29	0.38	0.35	0.42	-0.10	-0.15	-0.34	-0.15	-0.10	0.46
Connectivity % (August 2016)	0.38	0.16	0.21	0.35	0.42	0.19	0.13	0.45	0.33	0.59	0.40	0.22	0.48	0.12	0.23	0.32	0.10	0.05
Coefficient of uniformity (August 2016)	-0.42	-0.40	-0.34	-0.22	-0.50	-0.14	-0.43	-0.46	-0.33	-0.48	-0.34	-0.23	-0.12	0.09	0.18	-0.09	0.06	0.05
Available N (kgN/ha) SUM	-0.23	-0.16	-0.16	-0.19	-0.19	-0.08	-0.09	-0.21	-0.24	-0.10	-0.29	-0.03	-0.11	0.08	0.03	0.27	0.26	-0.04
Moisture content % (December 2015)	-0.19	-0.49	-0.06	-0.32	-0.36	-0.34	-0.27	-0.32	-0.28	-0.22	-0.22	-0.20	-0.12	0.12	0.22	0.22	0.04	0.13
Moisture content % (March 2016)	0.02	-0.17	0.01	-0.33	-0.09	-0.17	0.09	-0.15	-0.17	-0.04	0.08	-0.08	-0.34	-0.09	-0.12	0.05	0.10	-0.05
Moisture content % (June 2016)	-0.01	-0.01	0.05	-0.19	0.02	-0.24	0.17	-0.01	-0.02	0.03	0.18	0.02	-0.23	0.29	-0.07	-0.03	0.19	-0.07
Moisture % (August 2016)	-0.31	-0.07	-0.15	-0.23	-0.09	-0.18	-0.32	0.17	0.11	0.19	0.25	0.30	0.30	-0.13	-0.33	-0.02	-0.30	0.10
Soil moisture content (%), 0-5 cm (December 2015)	-0.30	-0.42	-0.20	-0.09	-0.27	-0.34	-0.31	-0.22	-0.31	-0.17	-0.37	-0.19	-0.03	0.53	0.07	-0.16	-0.07	0.09
Soil moisture content (%), 0-5 cm (March 2016)	-0.39	-0.14	0.04	-0.15	-0.24	-0.29	-0.25	-0.17	-0.15	-0.14	-0.18	-0.03	0.18	0.34	0.19	-0.11	-0.19	-0.02
Soil moisture content (%), 0-5 cm (June 2016)	-0.23	-0.15	-0.13	-0.14	-0.26	-0.38	-0.17	-0.04	-0.11	-0.03	-0.09	0.08	0.06	0.22	-0.08	-0.30	-0.18	0.28
Soil moisture content (%), 0-5 cm (August 2016)	-0.20	-0.26	-0.04	-0.02	-0.16	-0.45	-0.15	-0.10	-0.08	-0.13	-0.09	-0.01	-0.11	0.21	0.06	-0.17	-0.10	0.39
Plant population (plant m ⁻²)	-0.35	-0.14	-0.23	-0.47	-0.28	-0.13	-0.30	-0.10	0.11	-0.11	-0.02	0.10	-0.49	-0.38	-0.59	-0.35	-0.15	0.08
yield t/ha (combine)	-0.57*	-0.28	-0.03	-0.18	-0.42*	-0.25	-0.46*	-0.06	-0.13	-0.13	-0.10	0.08	-0.02	-0.19	-0.26	-0.36*	-0.30	0.36*
	Shear strength (Dec 2015)	Shear strength (March 2016)	Shear strength (June 2016)	Shear strength (August 2016)	Penetration resistance (0-10 cm) (December 2015)	Penetration resistance (0-10 cm) (June 2016)	Penetration resistance (0-10 cm) (August 2016)	Penetration resistance (10-20 cm) December 2015	Penetration resistance (10-20 cm) (June 2016)	Penetration resistance (10-20 cm) (August 2016)	Penetration resistance (20-30 cm) December 2015	Penetration resistance (20-30 cm) (June 2016)	Penetration resistance (20-30 cm) (August 2016)	Bulk density (December 2015)	Bulk density (March 2016)	Bulk density (June 2016)	Bulk density (August 2016)	Pore number (August 2016)

Pore Area (August 2016)	1																
Pore Size (August 2016)	0.55	1															
Porosity % (August 2016)	0.92	0.56	1														
Connectivity % (August 2016)	0.38	0.71	0.43	1													
Coefficient of uniformity (August 2016)	0.10	0.00	0.13	-0.09	1												
Available Nitrogen (kgN/ha) SUM	-0.30	0.14	-0.16	-0.07	-0.15	1											
Soil moisture content (%) (December 2015)	-0.07	0.23	0.02	0.31	0.45	0.18	1										
Soil moisture content (%) (March 2016)	-0.12	0.08	0.01	-0.01	-0.02	0.43	0.42	1									
Soil moisture content (%) (June 2016)	0.15	0.17	0.33	0.00	0.12	0.10	0.18	0.59	1								
Soil moisture content (%) (August 2016)	0.21	0.02	0.22	0.07	0.35	0.03	0.05	0.16	-0.11	1							
Soil moisture content (%), 0-5 cm (December 2015)	0.29	0.26	0.30	0.05	0.25	-0.06	0.10	-0.31	0.20	-0.22	1						
Soil moisture content (%), 0-5 cm (March 2016)	0.17	0.18	0.11	-0.10	0.28	0.02	-0.04	-0.36	0.04	0.01	0.52	1					
Soil moisture content (%), 0-5 cm (June 2016)	0.36	0.13	0.32	-0.02	-0.03	-0.10	-0.02	-0.26	0.16	-0.22	0.62	0.67	1				
Soil moisture content (%), 0-5 cm (August 2016)	0.09	0.11	0.04	-0.06	-0.07	0.00	0.07	-0.29	0.14	-0.46	0.56	0.50	0.67	1			
Plant population (plant m ⁻²)	0.09	-0.38	0.13	-0.44	-0.04	-0.19	-0.24	0.06	0.09	0.08	-0.19	-0.32	-0.06	-0.19	1		
yield t/ha (combine)	0.39*	-0.02	0.16	-0.16	0.24	-0.10	-0.01	-0.09	-0.32	0.56*	-0.12	0.22	0.07	-0.15	0.28	1	
	Pore Area (August 2016)	Pore Size (August 2016)	Porosity % (August 2016)	Connectivity % (August 2016)	Coefficient of uniformity (August 2016)	Available nitrogen (kgN/ha) SUM	Soil moisture content (%) Soil profile (December 2015)	Soil moisture content (%) Soil profile (March 2016)	Soil moisture content (%)Soil profile (June 2016)	Soil moisture content (%)Soil profile (August 2016)	Soil moisture content (%)in the upper 5 cm (Decemb er 2015)	Soil moisture content (%)in the upper 5 cm (March 2016)	Soil moisture content (%)in the upper 5 cm (June 2016)	Soil moisture content (%) in the upper 5 cm (August 2016)	Plant population	yield t/ha	

Organic matter values are not included in this matrix. Having them included, reduced the number of observation from 24 to 9 as rows with missing values were not counted. The critical value is 0.33 (n=24, $P<0.1$). (*) refers to significant correlation.

Table 2-7. The output of the regression analysis factor between triticale yield and soil properties.

Estimates of parameters				
Parameter	Estimate	s.e.	t(21)	t pr.
Constant	3.55	1.76	2.02	0.06
Soil moisture content % (August 2016)	0.29	0.11	2.52	0.02
Soil shear strength (December 2015)	-0.04	0.02	-2.63	0.02

2.4 Discussion

2.4.1 Changes in the soil physical properties:

2.4.1.1 Bulk density, shear strength and penetration resistance

Cultivation techniques had a significant effect on the soil physical properties. NT created a more compacted soil with higher bulk density and shear strength compared to MT and PL in the upper 5 cm of the soil. This was accompanied by an increase in the soil penetration resistance in the upper 30 cm of the soil surface of NT and MT compared to PL. This supports the findings of [Comia et al. \(1994\)](#) and [Filipovic et al. \(2006\)](#) who found that soil had higher compaction levels under reduced tillage than ploughed-based tillage. Though the results of this research do not agree with [Rusu et al. \(2009\)](#) and [Calegari et al. \(2010\)](#) who reported that reduced tillage forms did not increase soil strength indicators.

2.4.1.2 Soil organic matter

Soil organic matter was affected by tillage only in the upper 5 cm of the soil profile. The accepted view is that NT generates higher concentrations of organic matter resulting from a high level of plant residue left on the soil surface as stubble ([Mulumba and Lal, 2008](#)). Thus, incorporation of plant residues into the soil surface should increase organic

matter levels. [Reicosky et al. \(1995\)](#) found a strong linear relationship between the amount of residues and soil organic matter and a weak relationship between the type of the residues and the soil organic matter, but [Doan et al. \(2005\)](#) found that the type of the plant residues is important as legumes' had a more rapid positive impact on soil organic matter than other crops.

In our study, the similarity in soil organic matter content between the different treatments could be attributed to the time taken for straw to decompose compared to green leaves ([Giller et al., 2009](#)). Green parts of plant contain a high proportion of water that encourages the decomposition. The time needed for plant residue decomposition is crucial. [Kooistra et al. \(1989\)](#) noted that SOM increased just 0.5% after 19 years of high inputs of organic matter in wet weather conditions of the Netherlands. In a ploughed soil, the increase was 25% in the upper 5 cm of the soil after 12 years of plant residue incorporation and 20% in the upper 30 cm of the soil in similar conditions of Germany ([El Titi, 1991](#)).

[Giller et al. \(2009\)](#) attributed the increase in SOM to the residue retention more than lessening the tillage intensity. In the Scandinavian countries, [Rasmussen \(1999\)](#) found that while plant residues increased SOM in the upper soil layer after a few years, reduced tillage did not influence this increase. Using the CENTURY and RothC models, [Farage et al. \(2007\)](#) predicted that there would be only a small increase ($0.1\text{--}0.2 \text{ t ha}^{-1} \text{ year}^{-1}$) in SOM accumulation when NT is undertaken. The two models predicted a larger increase in SOM accumulation when plant materials are incorporated in the soil such as the situation in the forests or when manure is incorporated into the soil surface. Our results support the importance of time required for changes in soil because of the plant

residue retention as no increase in the SOM was captured in the short term, the first two years.

Soil texture is a key factor for SOM accumulation. Reduced tillage increases the SOM content in finer-textured soils compared to sandy soils where physical protection for the organic matter is limited (Chivenge et al., 2007). In our experiment, the soil texture was a sandy loam which could have hampered the accumulation of the soil organic matter.

2.4.1.3 Soil moisture content

Average soil moisture content in the upper 5 cm of the soil surface was higher in NT and MT compared to PL. Infiltration rate increases when a high level of plant residues is retained on the soil surface as stubble. Also, these residues play a vital role in shading the soil, reducing evaporation rate compared to bare ploughed soils where large surface areas are exposed to the sun and wind (Mulumba and Lal, 2008). Another reason could be the improved soil structure in NT and MT as a result of fine aggregate formation. Our results showed that soil pores in NT and MT were similar in size compared to the pores in PL which had higher PSD_{cu} values. However, the difference could be as a result of the pressing process which followed the ploughing. Pressing creates fine aggregates which increase the small pores that hold more moisture than larger pores (Atkinson et al., 2009), consequently, the gravimetric water content is expected to be higher. (*Soil moisture content in the upper 30 cm of the soil surface is discussed below*).

2.4.1.4 Soil structure

Soil porosity

Our results show that soil porosity in the upper 10 cm was not impacted by residue retention or the cultivation systems. Many studies have found that NT and MT are associated with increased soil porosity because of the high organic matter ([Boatman et al., 1999](#)), but in our experiment, there was no difference in organic matter between treatments potentially due to the short duration. In several other studies, it was observed that NT causes a denser and less porous soil as the soil surface is less disturbed than ploughed soil, but this is not always the case. The upper 10 cm of the soil is exposed to disturbance during the drilling process ([Gajri et al., 2002](#)). The extent of the disturbance is affected by the spaces between the rows and the drill used. In this experiment, the space between the rows was narrow (15 cm), which means that the soil surface disturbance was relatively intensive and this might have lessened the differences between the tillage treatments. In addition, a winged tine was used and this would have increased the disturbance in the NT and MT compared to a knife tine ([Morris et al., 2007](#)). The changes in soil porosity over time is less likely to be because of an experimental error.

Pore size distribution PSD_{cu}

The ratio of large to small pores was higher in PL compared to MT and NT respectively. This agrees with the findings of [Lipiec et al. \(2007\)](#) who reported a positive linear relationship between PSD_{cu} and tillage intensity, they also observed that similar and smaller pores prevail in NT soil compared to MT and to a larger extent with PL soils.

Residue retention increased PSD_{cu}. This could be attributed to the effect of the plant residues in increasing the pore size. Increased soil organic matter usually increases soil porosity rate and increasing the aggregation of the soil particles (Dao, 1993). However, no changes in organic matter were observed, so it could not explain the difference in PSD_{cu}.

Average pore size

Residue retention increased average pore size. Usually, macro-aggregates (>250 µm) are formed around roots and coarse organic fragments (plant residues in the process of decomposition) whereas micro-pores (<250 µm) are formed by binding the smallest soil particles (clay, sand and silt) with microbial poly-saccharides (Rochester, 2011, Mangalassery et al., 2013). The pore spaces between macro-aggregates are larger than the micro-aggregates, which could indicate that the pore size would be larger when plant residues are added as they enhance the formation of macro-aggregates. Cultivation did not have a significant effect on the average pore size. This is in contrast to Lipiec et al. (2007) who found that NT causes smaller pores than MT and PL.

Overall, soil depth affects pore space in the soil when NT is undertaken. On different coarse soils and after 6 years of applying NT to grow barley (*Hordeum vulgare* L) in Denmark, it was found that the pore space was similar in the upper 5 cm of the soil, but there was less pore space in the depth between 5-10 cm (Rasmussen, 1984, Elonen, 1988). Our study contains data averaged over the upper 10 cm of the soil surface.

2.4.2 Plant population

The impact of the different cultivation systems on plant population varied between the two seasons. During the first season (wheat), the plant population in both of the reduced tillage forms was significantly higher than ploughing. In the following year, triticale plant population was higher in PL and MT soil compared to NT. The correlation matrix between the plant population and soil physical properties showed that plant population correlated positively with soil organic matter in the depth 15-30 cm, but negatively with soil bulk density and shear strength. While the increase in the soil bulk density and shear strength could hinder the emergence of the seeds, the organic matter in this depth might have reduced the compaction allowing the emergence to take place or maybe just reflected less organic matter in upper layers due to residue incorporation. In our experiment, the organic matter in the upper 15 cm of the soil surface did not seem to affect the emergence, but it was influential in the 15 - 30 cm. Our results agree with [Masle and Passioura \(1987\)](#) who found similar adverse effects for the soil bulk density and shear strength on wheat crop establishment due to decreasing the plant population and hindering the plant growth under NT.

Drilling in a loose soil leads to deep sowing and insufficient seed-soil contact, consequently, decreasing the emergence ([Håkansson et al., 2002](#)). The soil-seed contact influences the time for seeds to be imbibed with water ([Bordovsky et al., 1998](#), [Wuest, 2002](#)). [Nasr and Selles \(1995\)](#) found that a reduction in the wheat emergence happened when the soil bulk density was greater than 1.2 g.cm^{-3} . In our experiment, the soil bulk density during the triticale crop establishment (December 2015) was 1.33, 1.24 and 1.31 g.cm^{-3} in NT, MT, and PL respectively. As all of these values were more than 1.2 g.cm^{-3} ,

this means that the establishment may have been affected in all treatments with a higher effect in the NT as it had the greater bulk density. However, the differences in the plant count during the early stage might have changed over the course of the experiment due to several factors such as weather conditions, weeds and pests, consequently, the cultivation system may not have affected the final plant population (Whaley et al., 2000, Atkinson et al., 2007).

2.4.3 Yield

Overall, a yield between 5 - 7.5 t.ha⁻¹ of triticale is considered a high under the UK conditions (Nix, 2014). The average UK triticale yield was 8.1 t.ha⁻¹ (AHDB, 2016). When NT is undertaken, crop production is more likely to be variable (Knight, 2004, Jones et al., 2006a). This was supported in our experiment as winter wheat yield was not affected by the tillage treatments during the first year of undertaking NT, but in the following year, triticale yield was significantly lower in NT compared to MT and PL. This result does not support Pittelkow et al. (2015b) who found that during the first 1-2 years of undertaking NT, all crops had a reduction in yield except oilseeds and cotton. Our results are in accordance with Rasmussen (1999) who observed in field experiments and from farmers observations in wet and temperate conditions in Scandinavia that winter wheat (*Triticum* sp.) was the only crop in which crop yields of NT were similar to PL. Our experiment supports this observation, and it can be added that winter wheat yield in MT is also similar to both of NT and PL during the first year of the transition from PL to MT or NT. It is more likely that crop yield is also impacted by other factors such as the growing crops and weather conditions.

In a meta-analysis study, [Pittelkow et al. \(2015b\)](#) reported that NT caused 2.6 % reduction in wheat yield compared to PL, whereas the reduction was largest 7.5% in maize and 7.6% in rice, other miscellaneous cereals including triticale had larger reductions. Our results supported this finding as triticale yield was higher when the soil was ploughed. Triticale is sensitive to all types of reduced tillage (including NT and MT) ([Dzienia et al., 1995a](#), [Dzienia et al., 1995b](#), [Roszak et al., 1995](#), [Malicki et al., 1997](#)), however, we found that MT could be a good alternative to PL as MT did not affect the triticale yield.

Triticale's lower yield compared to the wheat could be attributed to unfavourable weather conditions. Those conditions are represented in low air temperature during the early stage of the triticale growth and in the springtime as well as high rainfall rate during the ripening stage (June 2016). These conditions might have caused greater grain loosening and increased the risks of mould, pests pathogens, and slugs ([Lal, 2011](#)). It is more likely that the high rainfall in June 2016 (153 mm) had adverse effects on the filling of the triticale grains. Also, as NT is associated with plant residue accumulated on the soil surface, it is more likely that waterlogging took place during this time ([Rusinamhodzi et al., 2011](#), [Zheng et al., 2014](#)). Similar results were reported by [Li et al. \(2007\)](#), [De Vita et al. \(2007\)](#) and [Zheng et al. \(2014\)](#) who found that plant residues in wet conditions reduce crop yield due to waterlogging. In Zimbabwe, it was found that NT fields yield more than PL in dry years, but in years when the rainfall rate was more than the normal average, NT cause a reduction in the yield ([Giller et al., 2009](#)). [Biamah et al. \(1993\)](#) attributed the ability of NT to cope with dry years to the plant residues that are accumulated on the soil surface, but in wet soils, NT reduces the yield due to

waterlogging. Furthermore, it is expected that during wet weather conditions, the phytotoxins production from the stubble would be higher than dry soils (Wuest et al., 2000).

As triticale yield was influenced by the tillage treatments in our field experiment, the relationship between triticale yield only and soil physical properties throughout the year is investigated in the remainder of the chapter below.

2.4.4 The relationship between soil physical properties and triticale yield

The correlation matrix showed that there was a positive relationship between the triticale yield and number of soil pores, pore size and moisture content (%) in August 2016. There was also a negative relationship between the yield and shear strength and penetration resistance (0-10 cm) in December 2015, bulk density in June 2016, and penetration resistance (0-10 cm) in August 2016. Factors which are negatively correlated with yield refer to increased soil compaction which may have caused the yield reduction. Wet conditions in June 2016 (160 mm rainfall average) seem to have affected the soil conditions obviously by increasing the bulk density in June. The regression model showed that the triticale yield was significantly influenced by the soil shear strength in December 2015 and by the soil moisture content in August 2016.

2.4.4.1 Soil shear strength and triticale grain yield

In this experiment, the yield was affected negatively by the increased soil shear strength. Soil shear strength was highest in NT therefore, it could be considered the main reason for the decrease in the yield under NT. High soil shear strength restricts water and air movement in the soil due to reduced porosity, consequently plant roots'

growth and penetration are hampered ([Indoria et al., 2017](#)). Another effect of the higher soil shear strength at this time could be the reduction of shoot production shown above, therefore, crop yield would be less ([Atwell, 1990](#)).

Soil shear strength effects vary according to the soil type. [Whalley et al. \(2008\)](#) found that the increase in the soil strength reduced the production of the dry matter yield on sandy soils, but not on loamy soils. Our results show that shear strength adversely affected the grain yield production also on sandy loam soil.

There is a strong relationship between soil shear strength and soil moisture content. Under UK temperate conditions, grain yield is constrained by the drying soil in spring and summer ([Foulkes and Sylvester-Bradley, 2001](#)). Any small reduction in soil moisture content during these times is found to be accompanied by an increase in soil shear strength ([Whalley et al., 2006](#)), consequently, this would adversely affect the grain yield. This confirms the findings of [Passioura \(2002\)](#) that soil strength has a crucial role in grain production exceeding the role of the soil moisture content only. However, [Materechera et al. \(1991\)](#), [Whalley et al. \(2006\)](#) and [Whalley et al. \(2008\)](#) stated that it is not distinct to what extent shear strength is a constraint for the plant growth as the effect of the soil shear strength was assessed independently from the water stress.

2.4.4.2 Soil moisture content and triticale grain yield

The regression model showed that there was a positive relationship between grain yield and soil moisture content in the upper 30 cm of the soil profile before harvest in August 2016. The model indicated that the water was less available for the crop under NT during the late stages of the growth. Shortage of water during the milk and dough development of the crop could have affected grain filling. The average soil moisture content was

lowest in NT during August 2016, this seems to have reduced the grain yield (see page 78). The rainfall rate was high in July 2016, thus, it is expected that the water movement in NT was restricted compared to other tillage treatments.

Sandy soils have less ability than clayey soil to conserve moisture. Previous studies on a sandy loam soil, same soil type in this experiment, found a reduction in yield when reduced tillage forms were undertaken ascribing that to the decline in soil hydraulic conductivity as the sandy soil has a low capacity to form an improved soil structure (Comia et al., 1994, Arvidsson et al., 2014, Riley et al., 2005).

Overall, the regression model confirms that both soil shear strength and moisture content are associated in their limiting effect on triticale crop yield. The response of the crops to soil conditions is complicated and it is difficult to identify whether the high soil strength or the low water content in the soil was the main reason for the yield reduction (Whalley et al., 2006).

2.5 Conclusions

Soil strength was different between the first and the second year of this experiment. Overall, NT increased soil strength as indicated by in greater soil penetration resistance, soil bulk density and soil shear strength. Unexpectedly, reduced tillage did not increase the soil organic matter in the tillage layer. Plant residue retention contributed less to soil properties compared to tillage-induced changes. The residue retention on soil properties may take greater effect over time.

During the first year of different tillage practices, wheat yield was not different between the treatments, but the triticale crop in the second year was adversely affected by NT

with no difference detected between MT and PL. According to the regression model, the reduction in triticale yield was due to greater soil shear strength in December 2015 and shortage in soil moisture in August 2016. The triticale plant count at growth stage 31 was significantly less in soil under NT practice due to high soil shear strength and bulk density during the crop establishment. All of these factors had the potential to a poor yield. It is also expected that the exceptional wet weather conditions during the late stages of the season might have decreased the grains' filling and increased the soil waterlogging in the non-tilled soil NT due to accumulation of the stubble. Plant residue retention did not influence yield of winter wheat or triticale, nor soil structure.

To be able to assess the changes in soil structure caused by the different tillage treatments and plant residue retention, long-term experiments are required allowing plant residues to decompose and take further effect. It is recommended that soil structure should be explored below 10 cm depth as in this study it was not enough to show the changes caused by the tillage or residue retention due to being immensely disturbed because of other reasons such as drilling. Further research is needed to explore the effect of the soil type on yield when different tillage practices are undertaken under the UK weather conditions.

3 Chapter 3: Short term impacts of different tillage practices and plant residue retention on greenhouse gas emissions

3.1 Introduction

3.1.1 What is the potential of reduced tillage to mitigate climate change?

Climate change results from increasing greenhouse gases (GHGs: CO₂, N₂O and CH₄) in the atmosphere, primarily because of anthropogenic activities such as fossil fuel burning and land use. In 2005, around 10-12% of the anthropogenic GHG emissions worldwide were from agricultural sources ([Smith and Olesen, 2010](#), [Smith et al., 2014](#)). [Tubiello et al. \(2013\)](#) reported that agricultural emissions increased by 1.1% annually between 2000 and 2010, reaching 4.6 Gt CO₂ yr⁻¹ in 2010 (up to 5.4–5.8 Gt CO₂ yr⁻¹ with emissions from biomass burning and organic soils included).

Reduced tillage (e.g. MT and NT) is a suggested way to mitigate GHG emissions from agriculture. Reduced tillage can increase soil organic matter content, enhance carbon sequestration, enhance biological activity, improve soil structure protecting it from erosion and improve aggregate stability as well as using less fuel ([Fernández et al., 2010](#), [Petersen et al., 2011](#), [Zotarelli et al., 2007](#), [West et al., 2002](#), [West and Post, 2002](#), [Six et al., 2000](#), [Kong et al., 2009](#), [Helgason et al., 2010](#)).

The effect of reduced tillage on soil varies according to the soil depth measured. [Hermle et al. \(2008\)](#) found that no-till led to carbon sequestration in the upper 50 cm of the soil over 20 years. [Baker et al. \(2007\)](#) observed that reduced tillage increases the carbon

sequestration near to the soil surface only while ploughing led to more uniform distribution of the organic carbon in the soil tillage layer (Campbell et al., 2000).

Reduced tillage can decrease CO₂ emissions and increase CH₄ uptake (Hermle et al., 2008). This climate change mitigation potential might be offset by increased N₂O emissions which have been found to increase with reduced tillage (Six et al., 2004a, Hermle et al., 2008, Chatskikh and Olesen, 2007). Quantitatively, CO₂ emission are higher than N₂O emissions, but N₂O has approximately 300 times greater global warming potential than CO₂ (IPCC, 2001). Regina and Alakukku (2010) reported that increased N₂O emissions have the potential to offset 75-310% of the climate change mitigation obtainable from the soil carbon sequestration. Increased N₂O emissions under reduced tillage is due to anaerobic conditions and formation of micro-sites aggregates (West et al., 2002, Hermle et al., 2008).

Tillage practices affect the geometry of the pore structure influencing the physio-chemical and hydro-thermal soil conditions which influence greenhouse gas exchange depending on different factors such as the climate variables, soil type and residue management through affecting the accumulation of the organic matter. To date, only a few studies have explored the relationship between soil architecture and the net balance of GHGs. The usage of X-ray Computed Tomography (CT), which is a non-destructive approach, provides high-resolution image information on soil structure, aggregation and pore characteristics (Mooney et al., 2006) which complement more traditional parameters such as shear strength and penetration resistance.

3.1.2 Short term versus long term impacts of reduced tillage

The impact of reduced tillage on soil respiration depends on the longevity of repeating the same tillage practice. A number of studies investigated the effects of the different tillage practices on soil GHG emissions after different periods. For example, CO₂ fluxes from no-till fields were higher than ploughed fields in Georgia after 5 years of the same tillage practices (Hendrix et al., 1988). In a 9-year-study in the United States (Texas), there were no differences in the annual CO₂ fluxes from different tillage systems (Franzluebbers et al., 1995b). Kern and Johnson (1993) advised that measuring soil fluxes after more than 5 years of reduced tillage was required to allow time for the changes in the soil structure to take effect. Thus, a number of studies attempted to explore the effects of the several tillage regimes on the GHG emissions after 4-5 years of the transition, e.g. Campbell et al. (1995) and Larney et al. (1997). A study by Mangalassery et al. (2014a) noted that NT increased the soil organic matter sequestration if it was undertaken for at least 5 years. The five year time is affected by many factors such as soil type and growing crops (Post et al., 2004). However, 5-year-time is a long time to start the measurement as changes in soil GHG emissions can be observed from the first year of the management change (Ellert and Janzen, 1999). For examples, in Ontario, it was reported that CO₂ fluxes during the first growing season were lower from NT fields compared to ploughing system. This difference did not appear in the second growing season and the emissions were similar among the different fields (Fortin et al., 1996). Overall, limited studies explored whether NT can influence GHG emissions during the initial phases of the transition (Powlson et al., 2014).

3.1.3 Plant soil system - net ecosystem fluxes

Several studies have investigated the GHG emissions from bare soil only or when grass was growing ([Oertel et al., 2016](#)). Both cases do not reflect the situation in the cereal crops which cover a large area of land. For example, in 2009, 3.1 million ha in the UK was planted with cereals ([Bell et al., 2014](#)). As different crops can affect the GHG emissions in different ways, exploring these differences is crucial to report which crops may cause lower impact on climate change ([Frank et al., 2015](#)). This can be done through measuring the net ecosystem exchange (NEE) which has three gross flux components namely: (1) photosynthesis (assimilation), (2) autotrophic respiration (plants) and (3) heterotrophic respiration (microbes) ([Frank et al., 2015](#)).

NEE is subject to environmental changes that affect soil and plants. For instance, changes in weather conditions may affect the assimilation of carbon by the plant through photosynthesis. These environmental changes could be the variability in clouds, precipitation, light, temperature, humidity and soil moisture ([Law et al., 2002](#), [van Dijk et al., 2005](#), [Yi et al., 2010](#)) which all impact photosynthesis and hence NEE ([Zeri et al., 2014](#)).

Gross and net emissions are affected by the management practices and growing crops ([Baker and Griffis, 2009](#), [Suyker and Verma, 2010](#), [Knox et al., 2016](#), [Dold et al., 2017](#)). Replacing a crop with another, irrigating, different nitrogen treatments, changing tillage depth are all factors that may modulate the rate of the photosynthesis and the annual soil carbon balance ([Reichstein et al., 2014](#), [Baldocchi et al., 2017](#)). Therefore, it is

important to measure GHG emissions from the entire soil-plant system and not only from bare soil.

3.1.3.1 Plant effects on CH₄ emissions (NEE-CH₄):

Net CH₄ emissions are influenced by vascular plants which control the CH₄ production, consumption and transportation (Joabsson and Christensen, 2001, Lai, 2009). Many studies reported a strong correlation between net ecosystem productivity (NEP) and CH₄ emissions (Whiting and Chanton, 1993, Dacey et al., 1994, Greenup et al., 2000) as photosynthates are important for CH₄ production (King et al., 2002, Christensen et al., 2003, Ström et al., 2005). A few studies attempted to investigate the contribution of the plants on CH₄ emissions on rice paddies (Minoda et al., 1996, Dannenberg and Conrad, 1999), peatlands (Christensen et al., 2003) and tundra (King and Reeburgh, 2002, King et al., 2002). However, more studies are required in the arable land of other regions alongside considering the effects of various plant species. Plant contribution to CH₄ emissions is considerable as it is estimated by 3-52% of the NEE-CH₄ depending on time of the year and applied treatments (Minoda et al., 1996, Dannenberg and Conrad, 1999).

Plants influence CH₄ emissions in a number of ways, (1) plants are a fresh carbon source to be metabolised by methanogenesis in the soil and release CH₄ (Hornibrook et al., 1997, King et al., 2002, Ström et al., 2005). (2) Wheat, triticale and other vascular plants act as a conduit through which CH₄ can be transferred from the soil anoxic zone to the atmosphere (Hornibrook et al., 1997, King et al., 2002, Ström et al., 2005). (3) Plant aerenchyma is expected to be a medium with which root ventilation takes place. In this case, oxygen leaks through the plant aerenchyma into the rhizosphere. This situation

could inhibit the methanogenesis and lead to CH₄ oxidation to CO₂ ($\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$) (Chanton and Dacey, 1991, Watson et al., 1997, Joabsson and Christensen, 2001).

3.1.3.2 Plant effects on N₂O emissions

Plants play a role in enhancing the N₂O emissions through several mechanisms. In wetlands, it was found that N₂O emitted from plants through the bark of the trees, suggesting that the aerenchyma of the bark could be the medium through which the N₂O diffuses (Chang et al., 1998, Rusch and Rennenberg, 1998, Yan et al., 2000, Smart and Bloom, 2001, Chen et al., 2002, Müller, 2003). In flooded rice fields, 87% of the N₂O emissions diffuse through the plants the contribution of the plants was up to 18% of the net emissions (Yan et al., 2000). In wheat, maize and soybean fields, the contribution of the plants to N₂O emissions varied between 11% and 63% (Chen et al., 2002, Zou et al., 2005). Under laboratory conditions, barley (*Hordeum vulgare*) and canola (*Brassica napus*) were found to be a conduit in which N₂O can be dissolved and released from the soil to the atmosphere (Chang et al., 1998). It was also reported that enzymes can form N₂O inside wheat leaves during the biological process of nitrite (NO₂⁻) photo assimilation. Around 5-6% of the total N₂O emissions from agricultural soil–plant systems, is estimated to be formed in this enzymatic method inside the leaves (Smart and Bloom, 2001, Hakata et al., 2003).

3.1.4 Gaps in the literature

The three GHGs were considered as part of this experiment following the recommendation of Robertson et al. (2000), Smith et al. (2001) and Soussana et al. (2007) that it is crucial to investigate the effect of the land use change on all of the GHG

at the same time. There are limited comparative studies exploring the effects of different tillage practices and plant residue retention on the net balance of GHG emissions. Most similar studies are from areas that have been under reduced tillage for more than 4 years. Limited studies explored the effects of these factors on climate change in the short term (1-2 years). Furthermore, no previous studies included plant components in the measurements of the emissions. The aim of this study was to determine if reduced tillage and plant residue retention reduce GHG emissions compared to conventional tillage and consequently if reduced tillage and plant residue retention play a role in mitigating climate change in the initial stages of the transition.

The objectives of this chapter were to:

1. Estimate the effects of the different tillage practices and the plant residue retention on soil GHG emissions.
2. Estimate the effects of the different tillage practices and plant residue retention on the Net Ecosystem Exchange (NEE).

3.2 Materials and methods

Study site, experimental design, treatments, measurements of soil physical properties and soil structure assessment are shown in chapter 2.

3.2.1 Gas sampling

GHG emissions were collected from the plots throughout the growing seasons of both crops; winter wheat and triticale. The gas samples were collected from:

- (1) Soil only to estimate the soil-atmosphere gas exchange (soil respiration).

- (2) Soil and plants together to estimate the Net Ecosystem Exchange (NEE) of the three target GHGs, respectively.

3.2.1.1 Collecting gas samples from soil only

In this experiment, measurements of the GHG emissions from soil started on day 1 after sowing the crop in each year. The measurements continued on day 14, day 28 and then monthly until crop harvest using the static chamber method. For this, opaque PVC black chambers (diameter: 6.5 cm) were used (Livingston and Hutchinson, 1995, Pihlatie et al., 2013). The chambers were inserted into the soil surface to a depth of 2 cm (the volume of the head space was around 0.33 dm³). No growing plants were left inside the chambers during the sampling period. The air into these headspaces was mixed before taking the samples with a 20 ml syringe at intervals of 0, 15, 30 and 60 minutes. The samples were taken by inserting the needle of the syringe through a rubber septum fixed to the top of each chamber. Samples were stored under-pressure pre-evacuated 20 ml glass vials (Exetainers, Labco, UK).

3.2.1.2 Collecting gas samples from soil-plant system

For measuring the Net Ecosystem Exchange, samples were collected from the soil and plants using transparent chambers. Chambers of three different sizes were used to accommodate plant growth during the season. The sampling started after crop emergence of each year, using previously designed transparent chambers (diameter: 7 cm) which were inserted into the soil surface down to 2 cm depth (the inner volume of every chamber was around 0.58 dm³).

As the plants grew, bigger chambers were installed with a ground base. After the soil preparation for every crop, 40 cm plastic ground ring base were pushed into the soil in each plot leaving 10 cm above the soil surface to fix the Perspex chambers on. The remaining 30 cm of the ground tubes, were left under the soil surface to prevent the air flow alongside the tillage layer which is 30 cm.

Perspex, transparent and portable headspaces were placed on the ground tubes for an hour through which the gas sampling took place at the intervals of 0, 15, 30 and 60 minutes. The plastic cylinders were moved from one plot to another after collecting the samples. The dimensions of the cylinders were: height 60 cm and 120 cm, diameter 30 cm to surround approximately 10 plants in maturity. Each one of these cylinders was provided with 2 computer fans to stir the gas inside before collecting the samples. The samples were taken from the top of the chamber through a sealed rubber septum fixed for this purpose. These chambers allowed measuring the net gas emissions from soil and plants inside. The gas samples were kept at a constant temperature of 24 °C until being analysed with a gas chromatograph (GC) equipped with a thermal conductivity detector (TCD), flame ionization detector (FID) and an electron capture detector (ECD) (GC-2014, Shimadzu). The carrier gas used was nitrogen. The GHG fluxes were calculated using equations (3 and 4). A time series data was used for obtaining a linear response used for calculation. The gas data was converted from volume per volume (ppm) to mass per weight using the molecular weight of each gas and the ideal gas equation (Denef et al., 2007).

$$N = PV/RT$$

(Equation 3)

N: number of moles of CO₂, N₂O and CH₄

P: atmospheric pressure

V: the volume of the headspace dm³

R: the ideal gas constant (0.08205746 L atm* K⁻¹ mol⁻¹)

T: the temperature of sampling (273.15 + room temperature in °C)

$$E = (NM/AT) 1000$$

(Equation 4)

E: is the flux of each gas in mg m⁻² h⁻¹

N: number of moles of CO₂, N₂O and CH₄

M: the molar weight of CO₂, N₂O and CH₄

A: an area of the soil used

T: time in hours (h)

The transparent chambers measured the net ecosystem exchange NEE between the ecosystem and the atmosphere. During the day, photosynthesis offsets soil and aboveground plant parts' respiration (Ryan and Law, 2005).

3.2.2 Statistical analysis

Using GenStat (17th Edition, VSN International Ltd, UK) analysis of variance (ANOVA) was applied to explore the effects of the different tillage practices and residue retention on the GHG emissions and soil physical properties. During the analysis of the gas fluxes, treatments were uploaded as factors (cultivation*residues*year/time) and the block

* The standard atmosphere (symbol: atm) is a unit of pressure equal to 101325 Pa or 1013.25 hecto-pascals or milli-bars.

structure was as (block/residues/year) so that the annual changes in the emissions could be explored. Prior to the statistical analysis, the readings were checked for normality using Shapiro-Wilk test in GenStat. The normalisation was checked for each treatment separately.

To account for interdependence of the soil physical properties data over time, repeated measurement model in ANOVA was used to consider the data at different time points ([Sommer et al., 2014](#)). Depth was added as a factor when required. For the analysis of the penetration resistance at a single time point, split-split-plot design model was performed. The treatments were residues*cultivation*depth. The treatment structure was; residues in the main plot, cultivation in the sub plot and depth in the sub-sub plot. To investigate the effects of the treatments on GHG emissions, general ANOVA was used. The treatments were residues*cultivation*year/time. The block structure was block/residues/year.

To predict the best model describing the GHGs fluxes, a multiple linear regression analysis was used. The maximal model entailed all the physical properties studied in this experiment and the dry biomass production. This was followed by dropping the variables which did not contributed significantly to the model.

Changes in GHG balance (emission and uptake) can be attributed to soil physical properties and plant growth. This is more likely to be a multidimensional interaction affected by several factors rather than one factor only. To predict this balance, a multiple linear regression model was developed using a full set of data collected over 5 measurement time points. The X-ray CT soil structure data represents the upper 10 cm

of the soil surface. Shear strength, bulk density and moisture content were taken from the top 5 cm of the soil surface. Soil organic matter samples were taken from three depths, 0-5 cm, 5-15 cm and 15-30 cm. The gas emissions were taken from the soil surface using the chamber method.

3.3 Results

3.3.1 Weather conditions

Weather conditions during this field study are presented in chapter 2 (page 69-70).

3.3.2 Soil physical properties

Soil physical properties during this field study are presented in chapter 2.

3.3.3 Soil GHG fluxes

3.3.3.1 Carbon dioxide CO₂

3.3.3.1.1 Soil CO₂ fluxes

On average, CO₂ emissions were highest in NT at 230.7 mg m⁻² hr⁻¹ compared to the MT which was 204.4 mg m⁻² h⁻¹ and PL which had the average value of 199 mg m⁻² h⁻¹ ($P < 0.05$, Fig. 3-1). CO₂ emissions did not change significantly whether the residues were retained or removed.

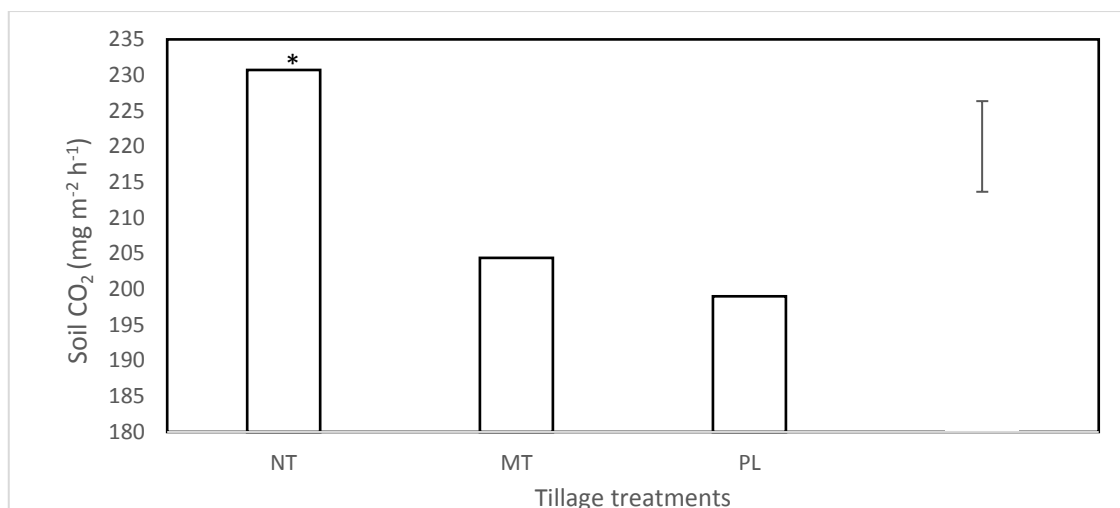


Fig. 3-1 Soil CO₂ emissions during the growing season of winter wheat and triticale. NT: no-tillage, MT: minimum tillage, PL: ploughing. Error bars represents standard error of differences S.E.D. Cultivation $P < 0.05$, $F_{(2,411)} = 3.56$.

The annual soil CO₂ emissions were lower in the first year than the second (172.1 mg m⁻² h⁻¹ and 273.2 mg m⁻² h⁻¹) respectively ($P < 0.001$). As expected the CO₂ emissions were lowest during winter, once temperatures increased in April, emissions increased. Over the first year, the highest emissions were detected in June 2015 at 411.1 mg m⁻² h⁻¹ while it was the lowest in December 2014 at around 90 mg m⁻² h⁻¹ ($P < 0.001$). Over the second year, the highest CO₂ emission was detected in July 2016 at 559.1 mg m⁻² h⁻¹ and the lowest was 114.6 mg m⁻² h⁻¹ in February 2016 (Fig. 3-2).

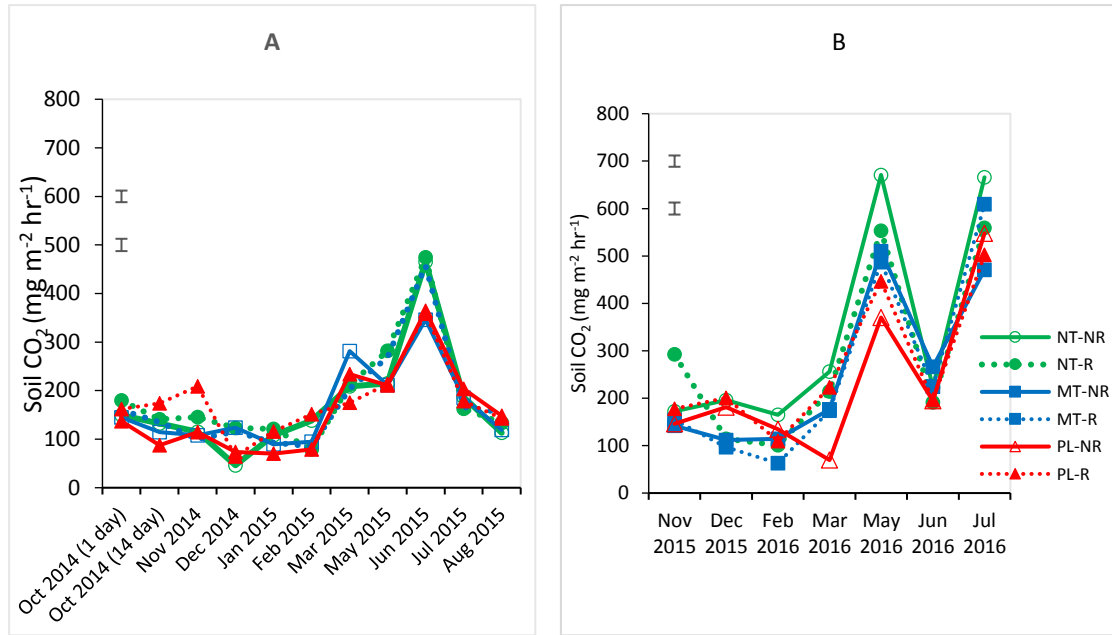


Fig. 3-2 Soil CO₂ emissions as influenced by tillage treatments and residue retention during the growing seasons of winter wheat (A) and triticale (B). NT: no-tillage, MT: minimum tillage, PL: ploughing. R: plant residues retained and NR: plant residues removed. Error bars represent S.E.D for cultivation below and for year above, Year F (1, 411)=71.76, $P<0.001$. Cultivation: F (2,411) =3.56, $P<0.05$.

3.3.3.1.2 Soil-plant CO₂ (NEE-CO₂)

There were no significant effects of residue retention or tillage system on NEE-CO₂ while the interaction between residue retention and tillage system was significant (Fig. 3-3). In PL, residue retention decreased NEE-CO₂, while, in both of NT and MT, residue retention increased NEE-CO₂ ($P<0.05$). The lowest NEE-CO₂ was detected in both of NT and MT without residues at 106 mg m⁻² h⁻¹, and the emissions in PL without residues was the highest at 279 mg m⁻² h⁻¹. NEE-CO₂ was significantly different between the two years ($P<0.001$). NEE-CO₂ was highest during the triticale year at 278 mg m⁻² h⁻¹ compared to 123 mg m⁻² h⁻¹ during the winter wheat growth cycle (Fig. 3-4). During the first year, neither residues nor cultivation affected the NEE-CO₂, but in the second year, both of them had a significant effect. In the second year, PL caused the highest NEE-CO₂ (402 mg m⁻² h⁻¹) and NT had the lowest emissions (190 mg m⁻² h⁻¹), but emissions varied

considerably over time ($P<0.001$). The emissions had peaks at 859 and 1153 $\text{mg m}^{-2} \text{h}^{-1}$ from measurements that were taken when the soil was dry in August of every year, just before senescence and harvesting.

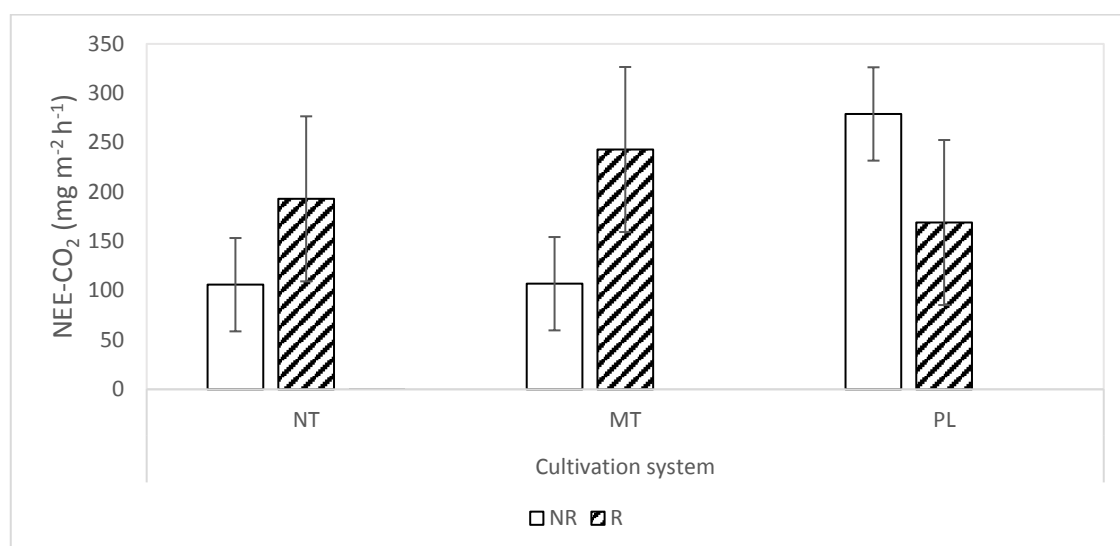


Fig. 3-3. NEE- CO_2 fluxes as influenced by the interaction between cultivation system and residue retention during the growing seasons of winter wheat and triticale. NT: No-tillage, MT: min-tillage, PL: ploughing, NR: plant residues retained, R: plant residues removed. Error bars represent the standard error of differences S.E.D. Interaction between tillage and residue retention was significant ($F_{(2,157)}=3.78$, $P<0.05$).

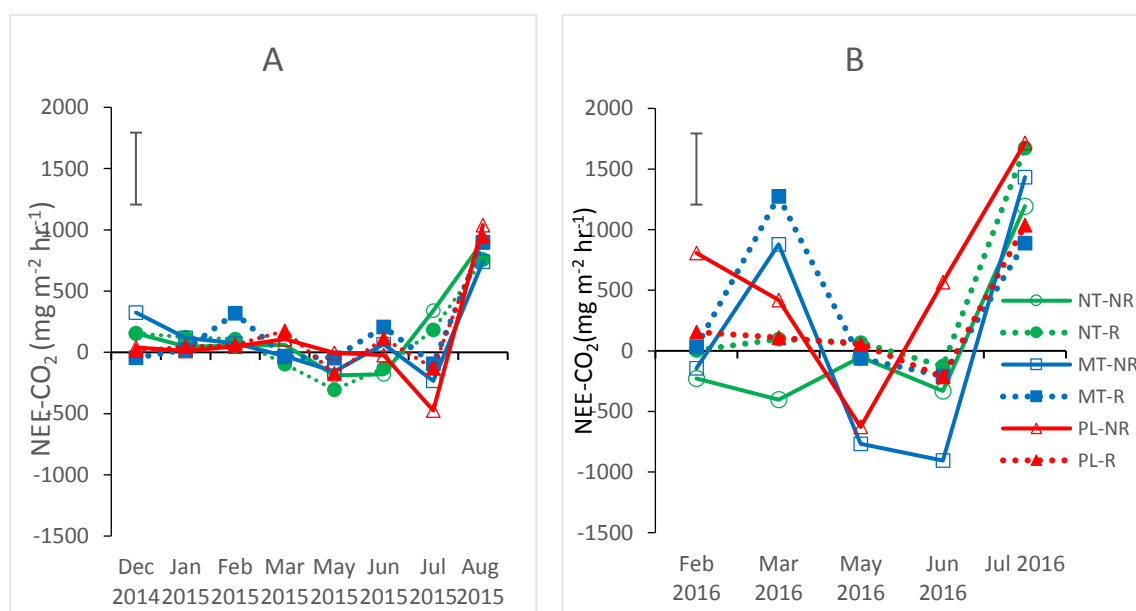


Fig. 3-4. NEE- CO_2 as influenced by tillage practices and residue retention during the growing season of A) winter wheat and B) triticale. NT: no-tillage, MT: minimum-tillage, PL: ploughing, NR: plant residues retained, R: plant residues removed. Error bars represent S.E.D for the interaction between cultivation, residue retention, date and year ($F_{(15,157)}=2.29$, $P<0.05$).

3.3.3.2 Methane (CH₄)

3.3.3.2.1 Soil CH₄ fluxes

A doubling of soil CH₄ uptake was found under NT and MT at $-0.02 \text{ mg m}^{-2} \text{ hr}^{-1}$ during the course of the experiment compared to PL where fluxes were $-0.01 \text{ mg m}^{-2} \text{ hr}^{-1}$ ($P < 0.05$, Fig. 3-5). Residue retention did not affect the CH₄ fluxes. CH₄ fluxes were not different between the two years, however, these fluxes varied within each year. During the low temperatures in October 2014, January 2015, and December 2015, soil CH₄ fluxes were low compared to when the weather was warmer (Fig. 3-6).

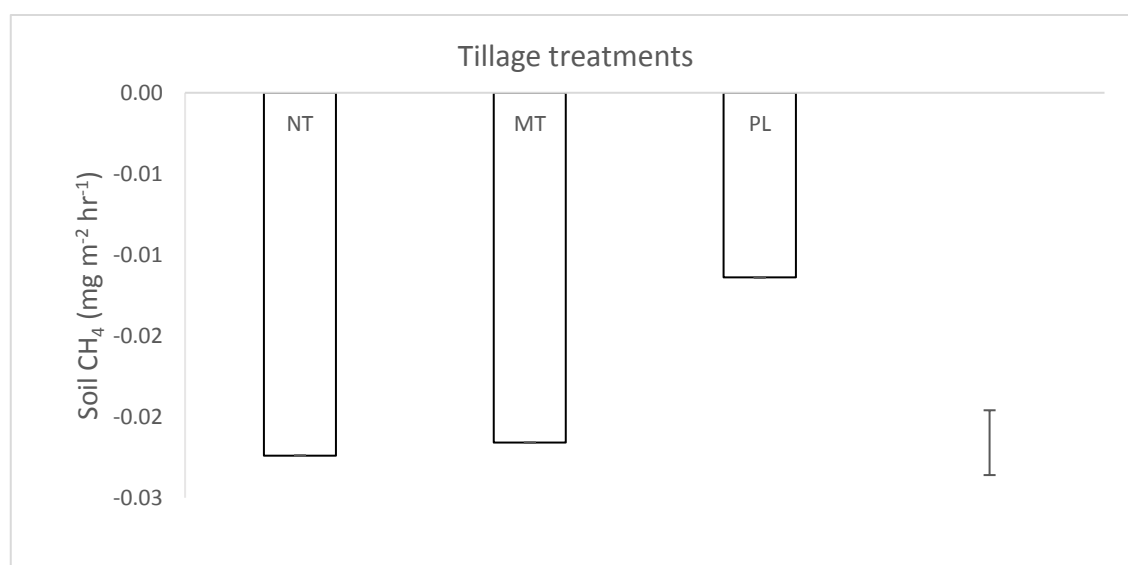


Fig. 3-5. Soil-CH₄ as influenced by tillage treatments during the growing season of winter wheat and triticale. NT: no-tillage, MT: minimum-tillage, PL: ploughing. Error bars represent the standard error of differences S.E.D. Cultivation ($F_{(2, 207)} = 4.95$, $P < 0.05$).

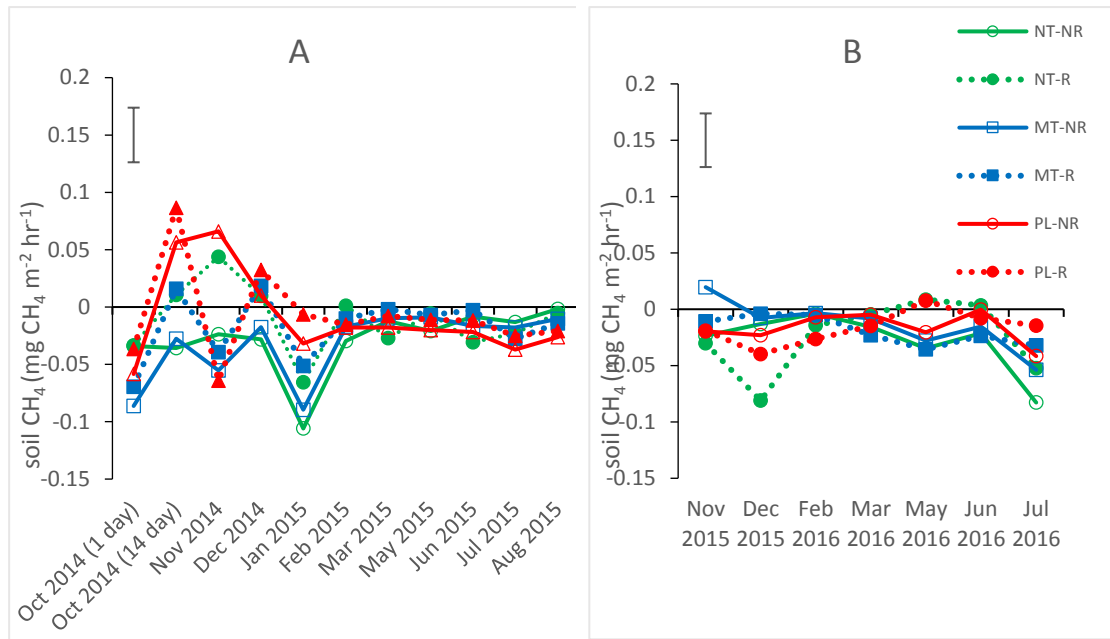


Fig. 3-6. Soil CH₄ emissions as influenced by different tillage practices and residue retention during the growing season of A) winter wheat and B) triticale. NT: No-till, MT: min-till, PL: ploughing, NR: plant residues retained, R: plant residues removed. Error bars represent standard error of differences S.E.D. interaction between residues, year, cultivation and time ($F_{(21,207)}=2.43$, $P<0.05$).

3.3.3.2.2 Soil-plant-CH₄ emissions (NEE-CH₄)

NEE-CH₄ uptake was also affected significantly by both cultivation and residue retention ($P<0.05$). NEE-CH₄ uptake was lowest in PL at $-0.04 \text{ mg m}^{-2} \text{ hr}^{-1}$ with significantly higher uptake in MT and NT at $-0.09 \text{ mg m}^{-2} \text{ hr}^{-1}$ and $-0.2 \text{ mg m}^{-2} \text{ hr}^{-1}$, respectively (Fig. 3-7).

Residue retention increased the CH₄ emissions from plant and soil ($P<0.05$). When the residues were retained, the NEE-CH₄ was $-0.07 \text{ mg m}^{-2} \text{ hr}^{-1}$, but it was $-0.16 \text{ mg m}^{-2} \text{ hr}^{-1}$ when the residues were removed. The net CH₄ uptake was highest in July 2015, May 2016 and June 2016 ($P<0.001$, Fig. 3-8).

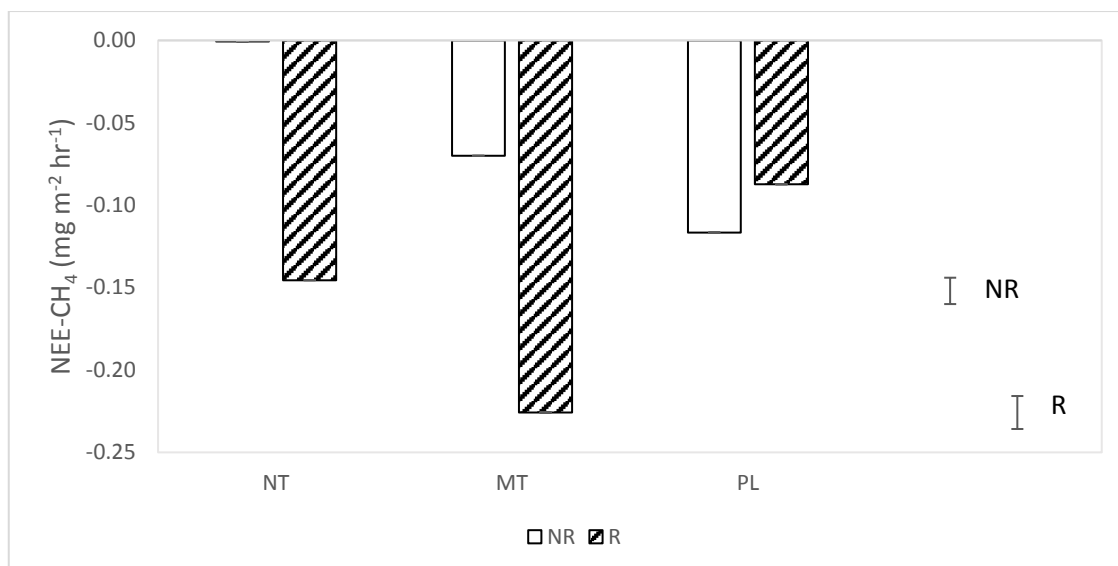


Fig. 3-7. NEE-CH₄ as influenced by tillage treatments and residue retention during the growing season of winter wheat and triticale. NT: no-tillage, MT: minimum-tillage, PL: ploughing, NR: plant residues retained, R: plant residues removed. Error bars represent the standard error of differences S.E.D. Cultivation ($F_{(2, 90)} = 51.21, P < 0.001$), Residues ($F_{(1, 90)} = 12.31, P < 0.05$).

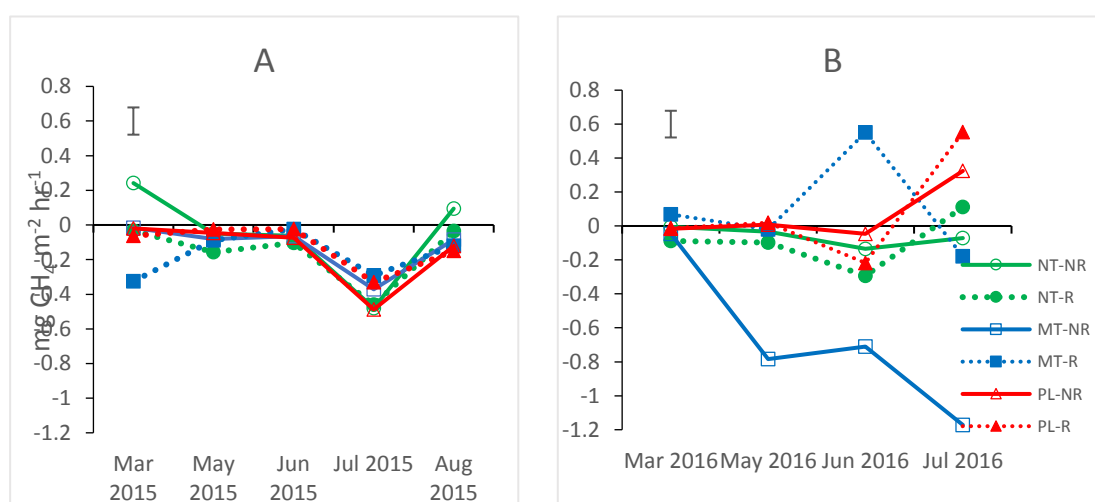


Fig. 3-8. NEE-CH₄ emissions as influenced by different tillage practices and residue retention during the growing season of A) winter wheat and B) triticale. NT: no-tillage, MT: minimum-tillage, PL: ploughing, NR: plant residues retained, R: plant residues removed. Residues ($F_{(1, 90)} = P < 0.05$) and Cultivation ($F_{(2, 90)} = 51.21, P < 0.001$).

3.3.3.3 Nitrous oxide (N₂O)

3.3.3.3.1 Soil N₂O fluxes

N₂O emission in the first year was 0.015 mg m⁻² h⁻¹ which was significantly less than the second year 0.021 mg m⁻² h⁻¹ ($P < 0.001$). The interaction between residue retention, cultivation and time of the measurements was significant ($P < 0.001$). In the first year, the lowest emission was detected in NT soil without residues and the highest one was captured in the NT when residues were retained. In contrast, during the second year, NT plus residues' soil had the lowest N₂O emissions and fluxes were highest in MT plus residues (Table 3-1). The changes in soil N₂O fluxes are outlined in (Fig. 3-9).

Table 3-1. The effects of the interaction between tillage, residue and time on soil N₂O fluxes $P < 0.05$ S.E.D= 0.025 (df= 61.52).

Cultivation	Residue retention	Year 1	Year 2
NT	No	- 0.0182	0.0322
NT	Yes	0.0344	0.0001
MT	No	0.0106	0.0142
MT	Yes	0.0245	0.0324
PL	No	0.0245	0.0196
PL	Yes	0.0169	0.0189

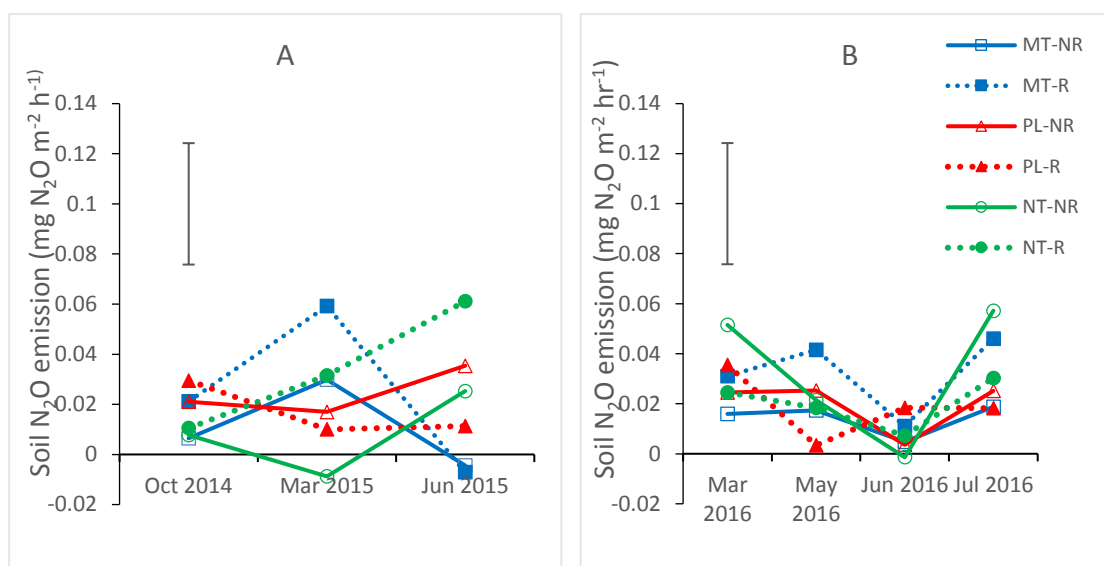


Fig. 3-9. Soil N₂O emissions as influenced by tillage treatments and residue retention during the growing season of A) wheat and B) triticale. NT: no-tillage, MT: minimum-tillage, PL: ploughing, NR: plant residues retained, R: plant residues removed. Error bars represent standard error of differences S.E.D (n=4). Cultivation*residues*year ($F_{(2, 102)} = 5.89$, $P < 0.05$).

3.3.3.3.2 Soil-plant N₂O (NEE-N₂O)

Cultivation had a significant impact on NEE-N₂O ($P < 0.001$, Fig. 3-10). MT released the highest NEE-N₂O at $0.14 \text{ mg m}^{-2} \text{ hr}^{-1}$, while it was lower in NT at $0.02 \text{ mg m}^{-2} \text{ hr}^{-1}$. In ploughed soil, N₂O uptake was observed at $-0.12 \text{ mg m}^{-2} \text{ hr}^{-1}$. The effect of residue retention was not significant. The residues*cultivation interaction had a significant impact on NEE-N₂O. N₂O uptake was $0.17 \text{ mg m}^{-2} \text{ hr}^{-1}$ in PL with residues retained, while the highest emission was detected in MT with residue retained at $0.15 \text{ mg m}^{-2} \text{ hr}^{-1}$.

There was no significant difference in NEE-N₂O between years. Associated with the fertilisation times within each year, NEE-N₂O was significantly higher ($P < 0.001$) in March 2015 at $0.1 \text{ mg m}^{-2} \text{ hr}^{-1}$ and in May 2016 at $0.18 \text{ mg m}^{-2} \text{ hr}^{-1}$ than other measuring time points. Comparing soil-N₂O flux and NEE-N₂O showed that the latter was up to 10 times

greater, which means that the plants increased N₂O emissions during both years. Fig.

3-11 shows the changes in all the treatments in over time.

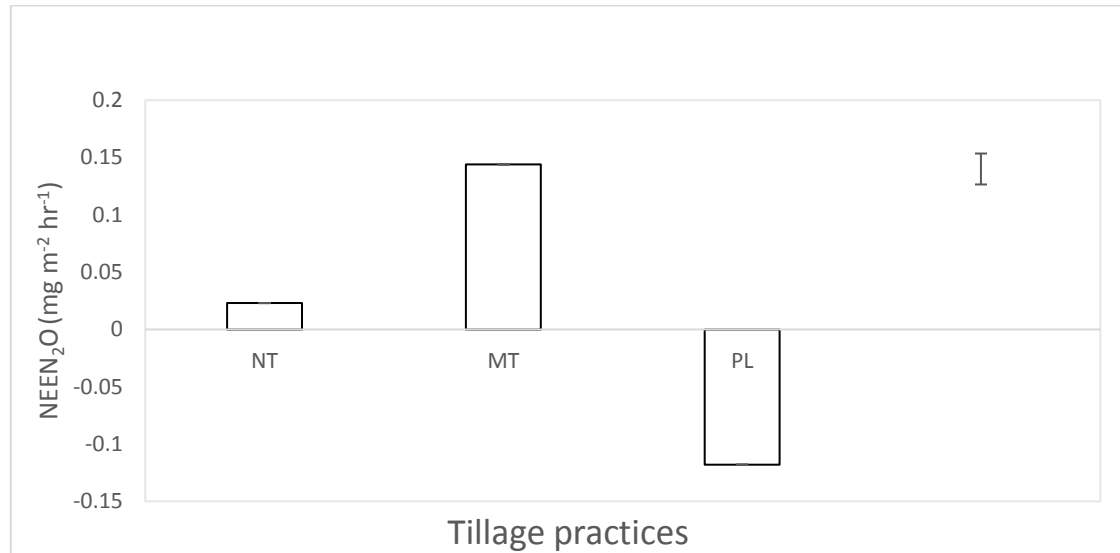


Fig. 3-10. NEE-N₂O as influenced by tillage treatments and plant residue retention. NT: no-tillage, MT: minimum tillage, PL: ploughing. Error bars represent the standard error of differences S.E.D. Cultivation*residues ($F_{(2, 73)} = 3.89$, $P < 0.05$).

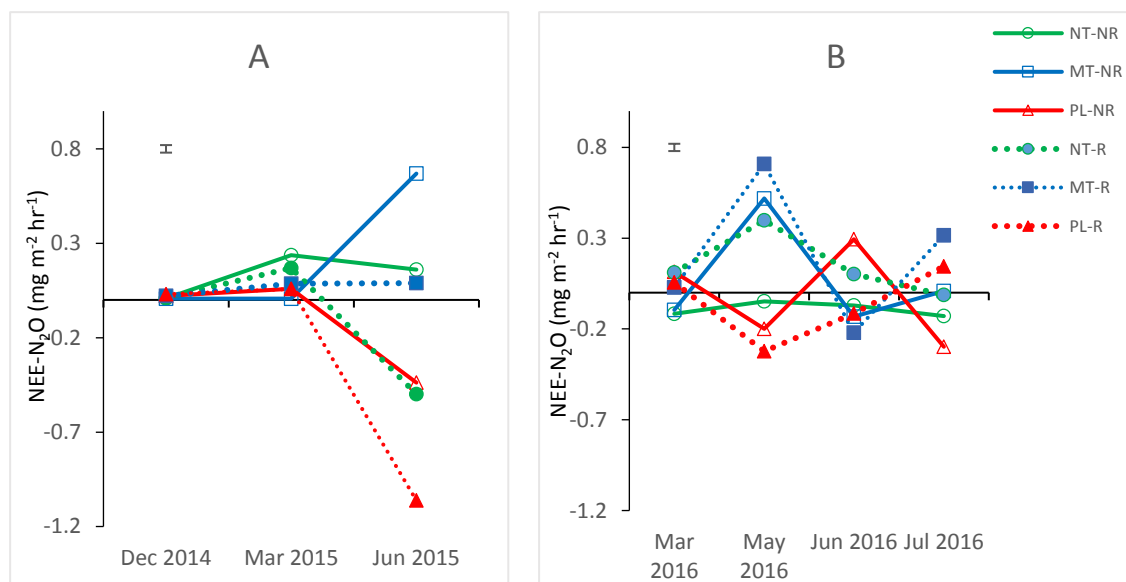


Fig. 3-11 NEE-N₂O as influenced by residue retention and tillage practices during the growing season of A) winter wheat and B) triticale. NT: no-tillage, MT: minimum tillage, PL: ploughing, NR: plant residues retained, R: plant residues removed. Error bars represent standard error of differences S.E.D. n=4. (Residues, Cultivation, year and time $F_{(3, 73)} = 8.86$).

3.3.4 Relationship between soil emissions and soil properties

Multiple regression found that 61.8% of the variation (with standard error of observations of 0.204, $P < 0.001$) in soil CO₂ flux can be predicted by soil porosity (%), soil moisture content (%), soil strength and soil pore connectivity (%) as presented in Equation 4. Fig. 3-12 (A, B, C, D, E) demonstrates the relationship between soil CO₂ emissions and these factors.

$$\text{Soil-CO}_2 \text{ (mg m}^{-2} \text{ h}^{-1}\text{)} = 5.03 - 1.4 \text{ soil bulk density} + 0.64 \text{ soil porosity} - 2.9 \text{ connectivity} + 0.68 \text{ soil moisture content \%} + 0.99 \text{ soil shear strength} \quad (\text{Equation 4})$$

Around 13.6% of the variation in soil-CH₄ flux can be predicted by soil shear strength only ($P < 0.001$, equation 5, Fig. 3-12 D).

$$\text{Soil-CH}_4 \text{ (mg m}^{-2} \text{ h}^{-1}\text{)} = 0.01 - 0.001 \text{ soil shear strength} \quad (\text{Equation 5})$$

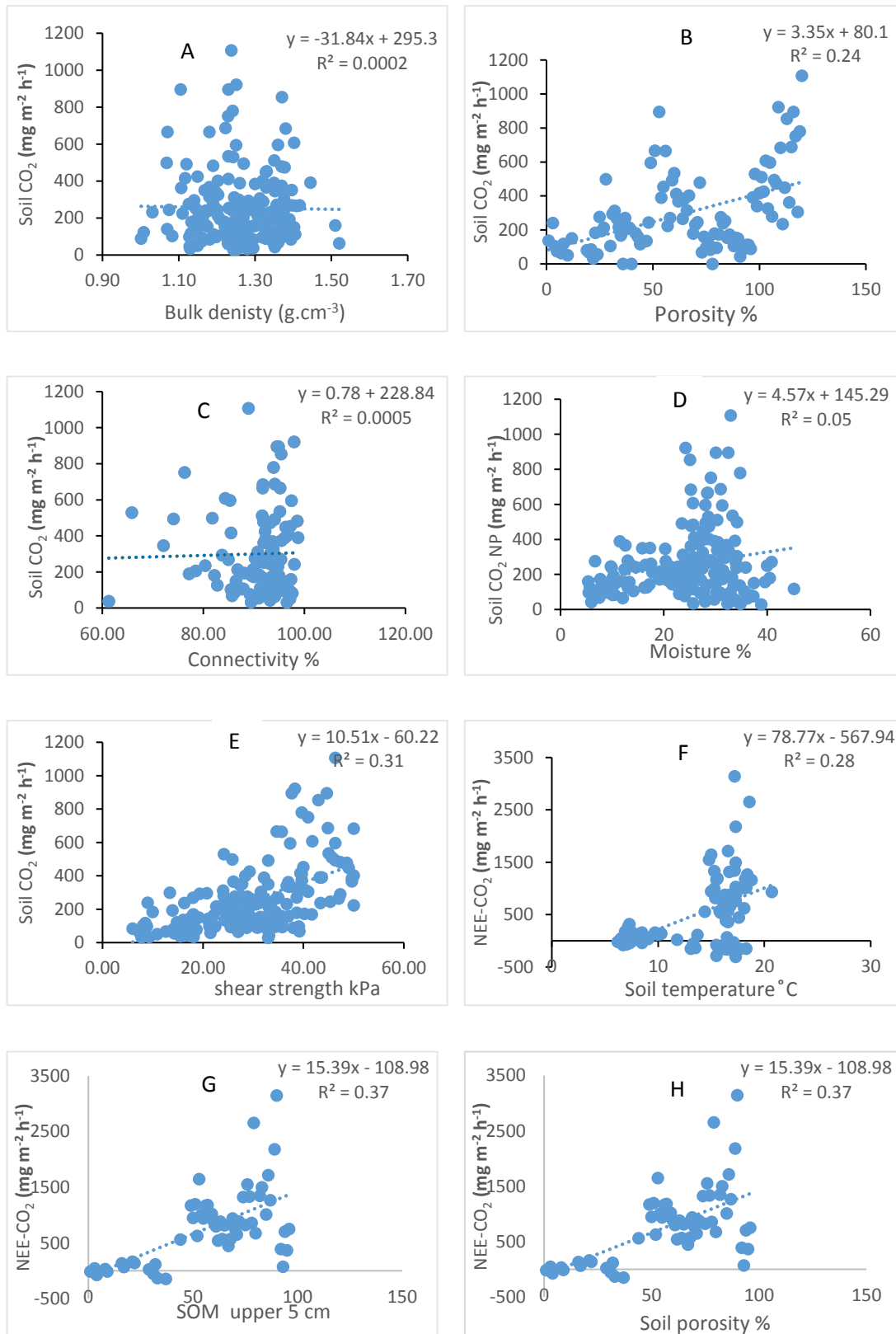


Fig. 3-12 Illustration of important relationships between soil physical properties and CO₂ release. A) soil bulk density and CO₂ emissions, (B) soil porosity rate and CO₂ emissions, (C) soil connectivity and CO₂ emissions, (D) soil moisture content and CO₂ emissions, (E) soil shear strength and CO₂ emissions, (F) soil temperature and NEE-CO₂, (G) soil organic matter (upper 5 cm of the soil surface), and (H) NEE-CO₂, and soil porosity (%).

3.3.5 Relationship between NEE and soil properties

Soil temperature explained 40.8% of the variation in the potential NEE-CO₂ as showed in equation 6 ($P < 0.001$, Fig. 3-13).

$$\text{NEE-CO}_2 \text{ (mg m}^{-2} \text{ h}^{-1}\text{)} = 95.3 \text{ soil temperature} - 663 \quad (\text{Equation 6})$$

The organic matter content in the 0-5 cm layer of the soil in addition to soil porosity rate % and pore connectivity ratio % were found to explain 36.7% of the variation in the NEE-CH₄ as in Equation 7 ($P < 0.05$). The standard error of observations was estimated to be 0.103. Fig. 3-13 outlines the relationships between CH₄ emissions and these factors.

$$\text{NEE-CH}_4 \text{ (mg m}^{-2} \text{ h}^{-1}\text{)} = 1.19 + 0.14 \text{ organic matter (0-5 cm)} + 0.25 \text{ soil porosity \%} - 0.03 \text{ soil pore connectivity \%} \quad (\text{Equation 7})$$

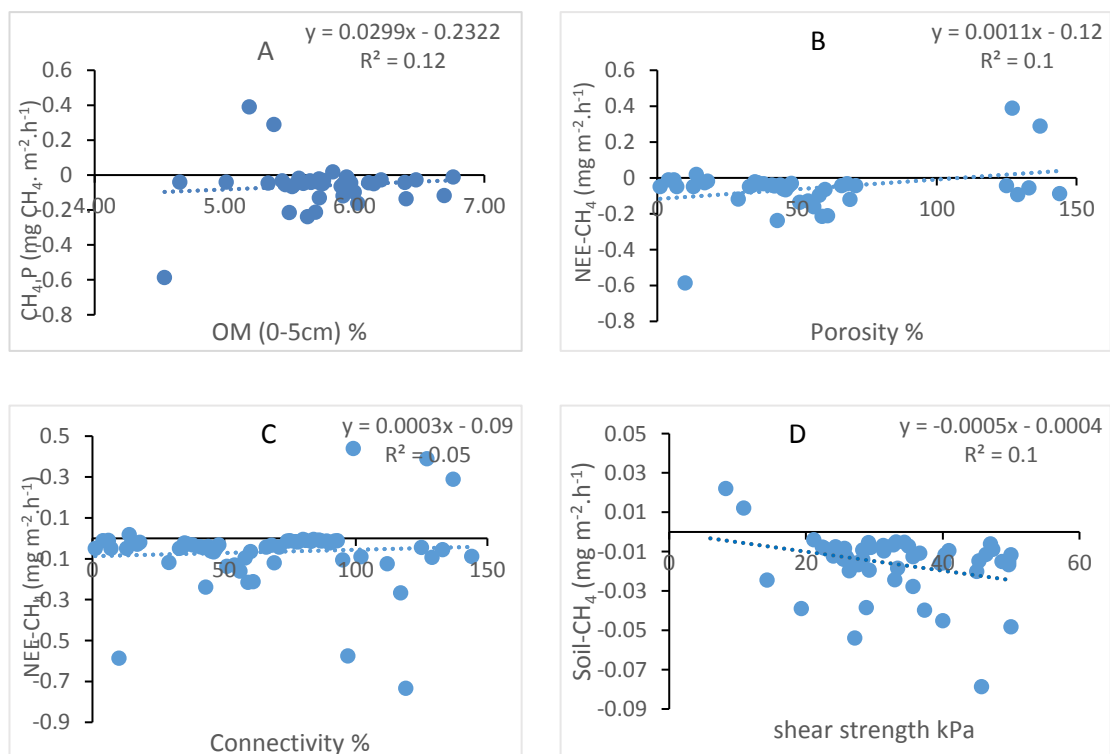


Fig. 3-13. Illustration of important relationships between soil physical properties and CH₄ fluxes: (A) soil organic matter in the upper 5 cm of the soil surface and soil CH₄ emissions, (B) soil porosity (%) and soil CH₄ emissions, (C) soil pore connectivity and soil CH₄ emissions and (D) soil shear strength and NEE-CH₄ emissions.

The regression model did not show any relationships between soil N₂O or NEE-N₂O with the soil physical properties.

3.4 Discussion

Overall, plant residue retention had limited effects on GHG fluxes compared to tillage during the first two years of the transition from conventional tillage to reduced tillage. Different tillage practices strongly influenced GHG emissions. However, CO₂ and CH₄ were more sensitive to changes in soil physical properties than N₂O.

3.4.1 CO₂ emissions

3.4.1.1 Soil CO₂

Unexpectedly, NT caused the highest soil CO₂ emissions compared to MT and PL. The annual average CO₂ emissions from NT was 230.7 (mg m⁻² h⁻¹) which was higher than 141 mg m⁻² h⁻¹ that was reported by [Mangalassery et al. \(2014a\)](#) when CO₂ emissions were measured in laboratory incubational conditions. Our result is in accordance with those of [Hendrix et al. \(1988\)](#), [Franzluebbers et al. \(1995a\)](#), [Bilandžija et al. \(2014\)](#) and [Bilandžija et al. \(2016\)](#) who attributed the increase in CO₂ emissions from NT to the higher moisture content in the soil surface which encourages biological activities. This may also explain our findings as we observed higher soil moisture content (0-5 cm) in NT and MT compared to PL. Indeed, the multiple linear regression model showed a positive relationship between CO₂ emissions and each of (1) soil moisture content (0-5 cm), (2) soil porosity and (3) soil shear strength. The increase in soil porosity might have increased the gas diffusivity from soil into the atmosphere, boosting the microbial decomposition of soil organic matter and enhancing the respiration of the organisms

(Udawatta and Anderson, 2008). In parallel, the increase in soil moisture content seemed to be associated with increased microbial activity and organic matter decomposition, consequently, higher GHG emissions. CO₂ emissions could increase due to higher soil shear strength as the contact between the plant residues and soil particles would be high enhancing the organic matter decomposition (Ussiri et al., 2009). Also, soil CO₂ emissions were negatively correlated with both soil pore connectivity and bulk density. This could be as higher bulk density and lower pore connectivity reduce the gas diffusion from soil into the atmosphere and reduce the moisture and air movement which govern the aerobic microbes' growth and the organic matter decomposition. The results of this model do not agree with Udawatta and Anderson (2008) and Beare et al. (2009) that PL increases CO₂ emissions due to increase in the movement of air and moisture, and the aerobic organisms respiration rate. Ball et al. (1999) found similar CO₂ emissions under NT, attributing the increase to larger pore size in NT at the upper soil surface. Overall, the increase in macro-pores number, organic matter accumulation and the biological activities in the upper soil surface are all factors which may increase the CO₂ emissions (Bronick and Lal, 2005, Zhang et al., 2007).

3.4.1.2 NEE-CO₂

Our study showed the lowest NEE-CO₂ was observed in NT and MT without residues and the highest emissions were detected in PL with residue retained. While NEE-CO₂ was not affected by any of the treatments alone, the trend was that PL caused higher emissions than both of the other reduced tillage forms. This suggests that there is a potential of reduced tillage to mitigate climate change as NEE-CO₂ was 21% and 33% less in MT and

NT respectively compared to PL. Similar results were found by [Bauer et al. \(2006\)](#) and [Chatskikh et al. \(2008\)](#).

In accordance with [Charles-Edwards and Rees \(1975\)](#) and [Rastogi et al. \(2002\)](#), the regression model showed that NEE-CO₂ was influenced by soil temperature only. This could be due to the effect of soil temperature on soil microbial activities, soil organic matter decomposition and root growth and respiration. Both tillage practice and residue retention affect soil temperature through altering soil organic matter content ([Schmidt et al., 2011](#)) and radiation ([Azooz et al., 1997](#)). However, [Beyaert et al. \(2002\)](#) found that crop residues are the dominant factor. In both NT and MT, crop residues are less incorporated in the soil and therefore, they might have reduced the heat input into the soil ([Azooz et al., 1997](#)), consequently reducing the NEE-CO₂. Whereas incorporating the plant residues in the soil remove this barrier between the soil and the atmosphere allowing, the heat exchange.

Soil temperature is interlinked with the atmospheric temperature. Thus, any changes in the atmospheric temperature will influence soil temperature. This effect was demonstrated in our experiment as NEE-CO₂ changed significantly over time. NEE-CO₂ was higher during the warm periods and also it varied with the phenological season/growth stage (pheno-phase) of the crops in accord with [Schlesinger and Andrews \(2000\)](#), [Amos et al. \(2005\)](#) and [Johnson et al. \(2007\)](#). This is associated with the increasing plant growth and photosynthesis rate which were high during the strong plant growth in spring and summer. In spring-time, neither soil temperature nor moisture would be a limiting factor for the emissions, but low temperature would be in

winter and low soil moisture in summer ([Ussiri and Lal, 2009](#), [Bajracharya et al., 2000](#), [Jacinthe et al., 2002](#), [Wan et al., 2005](#)).

3.4.2 CH₄ emissions

3.4.2.1 Soil CH₄

Both NT and MT had higher CH₄ uptake compared to PL. This positive impact of reduced tillage on climate change mitigation is in accordance with other studies such as [Mangalassery et al. \(2014a\)](#) which found that NT uptake was between 0.003 and 0.16 mg m⁻² h⁻¹. Our in-situ study showed a higher positive impact on climate change mitigation demonstrated in CH₄ uptake in reduced tillage. This supports the findings of [Liu et al. \(2006\)](#) that agricultural soil can be a CH₄ sink.

In agreement with [Wu et al. \(1992\)](#), [Schjønning and Rasmussen \(2000\)](#) and [Bhattacharyya et al. \(2006\)](#), our study suggests that soil shear strength is the best predictor for soil CH₄ fluxes. It is expected that increasing shear strength increases the functioning of the methanotrophic community, hence reducing CH₄ emissions ([Smith et al., 2001](#), [Lai, 2009](#)). Methanotrophs are prokaryotes that can grow aerobically or anaerobically, but tillage can change the oxygen and water balance reducing the soil methanotrophic population which requires a long time to recover ([Mosier et al., 1997](#), [Hütsch, 1998](#), [Nazaries et al., 2011](#)).

3.4.2.2 NEE-CH₄

There was an uptake of CH₄ from the three tillage treatments to different levels. Tillage system was an influencing factor on NEE-CH₄. The CH₄ uptake was highest in MT and lowest in PL. Also, residue retention increased NEE-CH₄ uptake significantly. Our results

are lower compared to results reported by [Schaufler et al. \(2010\)](#) who found that CH₄ flux in arable land in Denmark was 0.0014 mg m⁻² h⁻¹ and 0.0005 mg m⁻² h⁻¹ in grassland.

The regression model revealed a positive relationship between NEE-CH₄ and both organic matter in the soil surface (0-5 cm) and soil porosity (%), and a negative relationship between NEE-CH₄ and soil pore connectivity. The increase in the organic matter and porosity and the reduction in pore connectivity would be expected to increase soil moisture which is considered the single most important factor for soil emissions ([Oertel et al., 2016](#)). So, soil moisture content is important, but it does not show up in the model as it could be masked by soil organic matter in the same depth. Many studies reported that no-till enhanced the uptake of the CH₄, due to the continuity of the pores and the ecological niches for the methanotrophic bacteria. These two reasons increase the CH₄ uptake in no-till compared to ploughing ([Hütsch, 1998](#)) (reviewed in ([Six et al., 2004b](#))).

Vegetation enclosed in the chambers likely influenced CH₄ fluxes. Our results are in line with [Dalal and Allen \(2008\)](#) who found that when the plants are included in the measurement, the uptake of the CH₄ increased compared to soil-CH₄. This could be as a result of increasing soil CO₂ concentration due to increased root mass and respiration ([Dorodnikov et al., 2009](#)). When soil CO₂ increases, plant stomata close for a longer time increasing the moisture content in the soil surrounding the plants, consequently, CH₄ oxidation by methanotrophs increases ([Kim et al., 2014](#)). Also, through the plant aerenchyma, oxygen might have leaked into the rhizosphere inhibiting the methanogenesis and leading to CH₄ oxidation to CO₂ ([Chanton and Dacey, 1991](#), [Watson et al., 1997](#), [Joabsson and Christensen, 2001](#)).

3.4.3 N₂O emissions

3.4.3.1 Soil N₂O

There was no clear trend for the effects of the tillage treatments or the residue retention on soil N₂O fluxes. Our study did not support a number of studies in this field such as [Ball et al. \(1999\)](#), [Chatskikh and Olesen \(2007\)](#) and [Oorts et al. \(2007\)](#) which reported differences in soil N₂O fluxes according to different tillage practices. Our results disagree with an *in-situ* field study by [Regina and Alakukku \(2010\)](#) that NT causes between 21 to 86% higher N₂O emissions compared to ploughed soils. Our results do not support the result of a 30-year field study by [Oorts et al. \(2007\)](#) in which it was observed that N₂O fluxes were 39% higher in NT compared to PL. Also, our results contradict a laboratory experiment by [Mangalassery et al. \(2014a\)](#) which reported that NT increased N₂O emissions compared to PL. Most of the above studies have been carried out after few years of repeating NT.

In our study, there was a significant interaction between residue retention, tillage and year factors (residue retention*tillage*year). In the first year, it was noticed that N₂O was lowest in NT without residues and highest in NT with residue retention. In the second year, NT with residue retention had the lowest emissions and MT with residues had the highest emissions. This interaction can be attributed to two reasons; first, denitrification of crop residues accumulated on the soil surface. It is expected that ploughing pushes the plant residues down into the soil reducing denitrification level and making the N₂O production point down into the soil. In MT and NT, N₂O production point is more likely to be near to the soil surface due to residues' accumulation, and as the soil surface is permeable, then N₂O is more likely to be emanated into the above-

ground atmosphere. Having a crust near to the soil surface in ploughed soil, could make the soil surface impermeable and prevent the N₂O emanating and it might have led to its consumption by soil organisms (Luo et al., 2010b). Second, reduced tillage and residue accumulation might have increased emissions due to increasing water-filled-pore space, high concentration of mineral nitrogen (Oorts et al., 2007), reduction in air-filled porosity accompanied with low gas diffusivity (Chatskikh and Olesen, 2007), high soil moisture content (Blevins et al., 1971) and a denser soil structure (Schjønning and Rasmussen, 2000, Beare et al., 2009). All of these conditions might have increased anaerobic conditions required for denitrification (Ball et al., 1999).

3.4.3.2 NEE-N₂O

The highest NEE-N₂O was detected from the two reduced tillage types (MT and NT). Our results showed that plants growing in the field increased NEE-N₂O emissions. NEE-N₂O were ten times higher than soil-N₂O emissions. This result is in agreement with several studies such as Chen et al. (2002) and Zou et al. (2005) which observed that wheat plants increased N₂O emissions. Triticale seemed to have the same effect. Similar results were found by Chang et al. (1998) under laboratory conditions when barley (*Hordeum vulgare*) and canola (*Brassica napus*) were growing. Our finding is in support of Petersen et al. (2011) who observed that changes in N₂O emissions were related to crops rather than the soil tillage system. The authors reported that N₂O emissions were released from labile carbon and nitrogen of crops and plant residues. The effects of growing plants on NEE-N₂O could be attributed to a number of reasons: first, N₂O is the result of the denitrification of the nitrate and nitrification of ammonium which requires anaerobic conditions in the soil (Hénault et al., 2005). N₂O soil emissions increases in

the presence of the plant roots since they increase the availability of nitrate, labile C compounds, and O₂ ([Del Grosso et al., 2000](#)). Second, N₂O was measured shortly after fertilisation. Part of the fertilisers might stay stuck on the plant surfaces and chemically broken down before being absorbed through the plant surfaces. This might have increased the total N₂O emissions ([Snyder et al., 2009](#), [Guderian, 2012](#)). Third, plants contribute to total N₂O emissions as they can be a conduit in which N₂O dissolves and releases from the soil where it is formulated, into the atmosphere ([Chen et al., 2002](#), [Zou et al., 2005](#)). Furthermore, plants can be a source of N₂O through enzymes which form N₂O inside the plant leaves during the biological process of nitrite (NO₂-) photo-assimilation. This source accounts for around 5-6% of the total N₂O emissions from soil-plant systems ([Smart and Bloom, 2001](#), [Hakata et al., 2003](#)).

Unlike CO₂ and CH₄, the regression analysis does not show a relationship between the soil physical properties (including structure) and NEE-N₂O. This is in agreement with several studies such as [Drury et al. \(2003\)](#) and [Lee et al. \(2006\)](#) in which it was observed that soil structure did not regulate N₂O emissions. N₂O emissions were attributed to soil bio-chemical characteristics as they directly affect the denitrification bacteria ([Regina and Alakukku, 2010](#)). [Mangalassery et al. \(2014a\)](#) reported a strong relationship between N₂O and soil microbial biomass, this relationship was strengthened by the organic matter left on the soil surface when NT was undertaken. Microbial biomass production was not measured in our current study.

3.5 Conclusions

There is a high potential for climate change mitigation in the short term of undertaking NT and MT. In bare soil, NT increased CH_4 soil uptake and did not increase N_2O emissions as widely reported in many other studies (both of CH_4 and N_2O have higher warming effects than CO_2).

In soil-plant system, NT has positive effects as NT reduced CO_2 emissions and increased the CH_4 uptake. Moreover, NT did not increase N_2O as PL did. This means that N_2O was less likely to offset the significant decrease in CO_2 and CH_4 emissions.

Changes in the CH_4 and CO_2 have been found highly linked to the geometry of the soil architecture, but changes in N_2O was not. Measurement of the plant emissions should be counted in the future work to investigate the physiological impacts of plant on gas emissions.

4 Chapter 4: Farmer uptake of non-inversion tillage in the UK

4.1 Introduction

Tillage operations can be undertaken by various types of machines that manipulate soil. Soil manipulation equipment can cut, shatter, invert or mix the soil (Cannell, 1985). The aim of tillage is to optimise productivity through improving soil physical, chemical and biological properties (Gajri et al., 2002). Large developments have occurred in the tillage equipment industry to meet variable requirements in soil, climate and crop requirements. The depth of operations can be adjusted to suit soil conditions and tillage requirements as outlined in more detail below.

4.1.1 The Uptake of RT as an innovation in agriculture

There is a rapid recognition of the social aspects of agricultural innovation to understand the complexity in behaviours that influence the adoption of RT (Bitsch, 2005). It is believed that the awareness of the concerns and other farmers' perspectives should be included in any agricultural extension process (Pannell et al., 2006). A number of previous studies (Bultena and Hoiberg, 1983, Nowak, 1992, Roling and Wagemakers, 2000, Eckert and Bell, 2005, Bell, 2010) show that social aspects are highly important for adoption of RT as an agricultural innovation. Different places (regions and areas) have different processes for adoption of agriculture innovations, but in the case of tillage regime undertaken, a paradigm shift from ploughing to RT is required (Coughenour and Chamala, 2007). As deep tillage addresses problems such as weed management, fertiliser incorporation and others, the adoption of RT practices requires farm managers to learn how to overcome those challenges in other manners (Bultena and Hoiberg, 1983).

Farmers in other parts of the world have different incentives for RT uptake. For example, in Brazil, Australia and Midwestern area of the United States, RT is used to reduce soil erosion (Pimentel et al., 1995, Busscher et al., 1996, Derpsch et al., 2010). In San Joaquin Valley, California, RT is used to reduce the cost of fuel and labour cost required for tillage passes; farmers also retain the plant residues aiming to conserve soil water content rather than aiming to minimise erosion (Mitchell et al., 2007). According to a meta-analysis exploring the adoption of different best management practices, it was found that education level, farm size and other information such as capital, income, positive environmental attitude and environmental awareness are correlated with the adoption of agricultural innovation in the USA (Prokopy et al., 2008). In another study conducted in Iowa province of the USA, farmers' characteristics including age and education, and farm characteristics; type and size, varied between adopters and non-adopters (Pimentel et al., 1995). In addition to these factors, the environmental awareness and perceptions of soil and water situation were factors differentiating adopters from non-adopters (Korsching et al., 1983, Pimentel et al., 1995). In Ohio State in the USA, it was found that RT was used to lesser extent on large farms (Napier et al., 1984).

Farmers do not adopt different agricultural innovations at the same pace. Vanclay (2004) and Pannell et al. (2011) have recognised that farmers are quicker at adopting *less complex* innovations than the *more complex* ones. RT forms are considered complex practices and they require an extensive change in farm management. This could be attributed to the fact that RT forms are based on farmers' experiences and they are not disseminated sufficiently to farmers after being designed and tested by researchers and industry. Each farmer can adjust the RT practices they follow on their land based on the

local context (i.e. the crop varieties and types, machine availability and the location including soil type and land slope). In contrast to Rogers's model of innovation diffusion theory (1961), uptake of multifaceted and complex agricultural innovations cannot be easily predicted due to the many variables influencing the farmers' decision in the case of the RT. These variables influencing uptake include aspects involved in the process of adoption, such as the communication channels and the facilitation of ideas exchange, as well as the individual context and interpretation by the farmer. Therefore, the adoption of the RT practices is complicated compared to the adoption of other, arguably simpler, agricultural innovations. Thus, any successful extension work and innovation delivery would have to encompass these wider social and economic processes ([Fleming and Vanclay, 2009](#)). The adoption of new techniques in a farm business is in part based on farmer understanding of the techniques. Understanding farmers' perspective and challenges therefore represents an important area of study in order to incentivise the transition from inversion to non-inversion tillage. The aims of this chapter were to understand factors affecting farmers' uptake of RT and the challenges they face with respect to the adoption of RT. This chapter sought to address the following questions:

- What are the current tillage practices adopted in England?
- What proportion of farmers are practising NT, MT and PL?
- How many hectares are cultivated under each one of these practices?
- What are the characteristics of the farmers who have adopted RT practices?
- What are the farm / farm-level factors that influence RT adoption?
- Why is RT adopted to a lower extent than conventional deep tillage?

4.2 Materials and methods

In order to address the objectives of the chapter, a postal survey was undertaken on farmers across England following an approach used by [Townsend et al \(2016\)](#). This method was used to reach a large number of farmers within limited time gap, winter, within which less agricultural activities can be done. To achieve a sufficient number of data observations, the questionnaire was posted to 2000 farmers. This number is recommended as it reduces the error margin to about 2% ([Dillman et al., 2011](#)). According to [Defra \(2011\)](#), a sample of 2000 farmers represents almost 4% of the farms in these regions. To facilitate return of the completed survey, a pre-paid addressed envelope was provided to the farmer respondents.

To ensure that the terminology used in the questionnaire was appropriate for farmers, and to avoid vagueness in questions, prior to sending the finalised questionnaire to the 2000 farmers, 12 farmers and farm managers in Nottinghamshire and Leicestershire completed and provided feedback on a pilot questionnaire. A cover letter was prepared and tested along with the survey questionnaire (Appendix 1 and 2). The questionnaire was sent out in January 2016 as farmers were expected to be less busy with their practical farming activities at this time of year. During preparation of the questionnaire, previously published papers were reviewed to ensure comparability of data responses to previous research.

4.2.1 The participants

The addresses of the arable farmers were supplied by the company Experian whose database is built from the Yellow Pages and the Thompson Directory. The farmers'

names and addresses were chosen based on the activity type of the farmers. The company Experian provided a list of arable farmers.

4.2.2 The questionnaire

The questionnaire contained five main sections (Appendix 2). The sections complement each other, but each had a specific theme. The first section explored farm data including land holding size, farm type and location (county). According to the crop production report in England 2015-2016 the average size of cereal farms is 200 hectares (Lang, 2016). The following farm size options were specified in the questionnaire: (0 -50, 50-100, 100- 200, 200-400, more than 400 hectares). Farm type included the main farm types in England: combinable crops, general cropping, mixed farms (combinable crops and livestock) and livestock only. Respondents were asked to provide the location of their farms as the county within which their majority of the farming operations occur. County level information was later categorised as pertaining to a Government Office Region (GOR) (one of nine) and to European Union super region (one of three)². The second section explores farmer characteristics including age, gender, highest education qualification and the years of experience of managing the farm enterprise. The third section obtained responses about crop establishment and tillage practices for each crop grown, including the number of passes and tillage depth for each crop. To determine the areas of RT and ploughing, respondents were asked to note the proportional area of their land that they plough or cultivate through RT. Respondents were asked to note the crops they grow under each tillage practice. The fourth section sought data relating

² These align with the Defra Farm Business Survey.

to straw use and incorporation. The fifth section captured data on the barriers to adoption of NT and MT. Space was also provided at the end of the survey for respondents to provide further comments. For most questions, closed question formats were used with pre-determined possible responses for respondents to choose from. Pre-determined possible responses were taken from the tillage practices in the UK and Northern Europe literature including [Morris et al. \(2010\)](#). Space was additionally provided after each question for respondents to add other factors influencing their tillage practice decision making that were not listed as pre-defined possible responses.

4.2.3 Survey responses

By the end of April 2016, 479 replies (24% return rate) were received back from farmers. Only 371 have been considered in the analysis. The remaining responses (108) were discarded because of not being complete, respondents apologised for not answering surveys, or being received from respondents who had retired by the time of receiving the survey, plus livestock farmers who do not have any tillage practice. This number of responses is sufficient to obtain representative figures as it exceeded the number of observations in a study by [\(Townsend et al., 2016\)](#). This number (371) is higher than the arable farms used in the Farm Business Survey in England [\(Lang, 2018\)](#). The responses were categorised based on: prominent tillage system used; farm size; farm type; age; education level of the farmer; region in which the farm is located. Where respondents chose not to answer a question, this was defined as “*unknown*”. [Morris et al. \(2010\)](#) warned that contacting farmers through addresses taken from a commercial company, bias the questionnaire towards larger farms. [Lobley and Butler \(2010\)](#) note that typical responses to questionnaires are likely to be biased towards farmer respondents with

large farmed areas than the population overall; however they further note that this is an accepted form of response as large farms occupy large areas and therefore the responses received represent a more accurate analysis of the farmed area of interest (Lobley and Butler, 2010). This questionnaire was expected to be completed by a high proportion of farmer respondents irrespective of farm size as cultivation is an area of concern for all farmers.

4.2.4 The statistical analysis

The respondents were categorised on the basis of whether they were using RT or not in order to undertake non-parametric hypothesis testing and analyse the probability of uptake via logistics regression analysis.

Chi-Squared Analysis

Using Chi-squared tests, responses were analysed to test the hypothesis that there was no significant relationship between farmers' age, farmers' education, farm ownership, farm type, farm size and farm EU region location, to the response to the tillage practices undertaken.

The conceptual framework for the logistic regression model

The adoption of a new agricultural innovation or change in agricultural practice can be referred to by the extent of the continuous use of the new practice as the dependent variable. This is where the initial adoption decision is made, and this is where the efforts to change farmers' behaviours can be focused (Marra et al., 2003).

As noted above, RT in this study refers to manipulation of the soil surface during the seedbed preparation using non-inversion soil tillage equipment. For the purpose of

analysis, an adopter was defined as a respondent using RT to any extent (e.g. a small percentage of cultivated area to 100% of the cultivated area), and a non-adopter is referred to a respondent using plough-based cultivation only.

Making change in the field level management is based on farmers' perception of the new technology or updated method provided (Adesina and Zinnah, 1993). Wossink et al. (1997) believes that farmers are expected to have subjective assessments which could be the influencing drivers for adopting new policies in the level of the field management.

It is hypothesised that in addition to these perceptions, both farmer and farm characteristics can influence the farmer decision about using RT. The adoption of RT could be defined as occurring when the subjective adoption of PL becomes less than the usage of RT.

$$P(RT) = F(A, B, C, D, E, F, G, H)$$

P(RT): denote the farmer has adopted RT (1) or not (0), A: Farm size, B: Government Office Region (GOR), C: Farm type, D: Farm tenure, E: Age (year), F: Minimum experience (year), G: Gender, H: Highest education level.

To predict the likelihood of a farmer has adopting RT or not a logistic regression model was constructed. The logistic regression was used to explore the relationship between the dependent dichotomous variable RT and one or more of the nominal independent variables. The STATA (v14) statistical package was used. As a cumulative logistic probability function is assumed in the logit regression, so the model can be described as

Equation 8:

$$P(RT) = \frac{1}{1 + e^{-f(A,B,C,D,E,F,G,H)}} \quad (\text{Equation 8})$$

P (RT) the probability of RT adoption. The variables of the farmers and the farm data are described by a vector of variables.

4.2.5 Assessing the regression model

4.2.5.1 Wald test

To assess a multivariable survey logistic regression model, a Wald test is used. Wald test analyses if each variable should be included in the model or not (Bewick et al., 2005). It is used to choose the best combination of explanatory variables (Petrie and Watson, 2013). However, Agresti (2002) stated that the Wald test is not always reliable as it is influenced by the sample size and the likelihood ratio is recommended.

4.2.5.2 The likelihood ratio (LR) test

Within logistic regressions, the goodness of fit of the model is based upon a comparison of the relative likelihood ratio LR metrics from the fitted model, against a LR metric based on a model that contains only a constant as the independent variable. Hence, the LR aims to identify any differences between the fitted model and the simple model which contains only the intercept (Agresti and Kateri, 2011). The null hypothesis would be rejected if the LR test value is less than 0.05 (a significant result indicates poor prediction). This would indicate that the model does fit the data. When the LR co-efficient value is large, Bewick et al. (2005) have recommended using the LR test rather than other test such as the Wald test which does not always show the significance of the factors. However, in many cases these two tests have shown similar results (Engle, 1984, Agresti, 2002).

4.2.5.3 *The coefficient of determination (Nagelkerke, Cragg & Uhler's R^2):*

This test is employed to check how well the model represents the data. It is also called the multiple correlation co-efficient and it measures the variations in the response variable Y affected by the explanatory variables (Greene, 2000). The values of R^2 range between 0 (which means that there is no relationship between the dependent and the independent variables) and 1 (means that the relationship between them is extremely strong).

4.3 Results

4.3.1 Proportion of farms using NT, MT and PL

Out of the data from the 371 respondents with completed questionnaires, only two farmers (<1%) adopted NT only on all their arable land. Sixty-four farmers (17.3%) applied NT only on part of their area, 56 respondents (15.1%) were using NT on 50% or less of their area, and 42 were using NT on less than 30% of the holdings cultivated area. With respect to MT, 7.3% (27) of the respondents adopted MT on all their arable land, and 64.9% (214 respondents) adopted MT on some of their land (from 10 to 90% of the farm area). With respect to PL, our results show that 30.8% (114) of respondents did not adopt any form of RT (Table 4-1, Fig. 4-1).

4.3.2 The agricultural area under NT, MT and PL

The participants of this study collectively farm 118,713 ha which represents (2.64%) of the total arable crops area in the UK which was 4,505,000 ha in 2015³. The area under NT was estimated to be 8,238.5 ha (7.04%), area under MT is 55,747 ha (47.61%), and area under PL is 53,101 ha (44.35%) (Fig. 4-2).

Table 4-1 Number and percentages of farmers adopting different tillage practices.

Tillage system	Number of farms	%
NT only	2	0.54
MT only	27	7.30
NT and MT	14	3.78
<i>RT only</i>	43	12.05
PL only	114	30.81
NT and PL	14	3.78
MT and PL	164	44.32
NT, MT and PL	36	9.46
<i>Mixed of reduced tillage and ploughing</i>	214	59.66

³https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/486326/structure-jun2015final-uk-17dec15.pdf. Page 11.

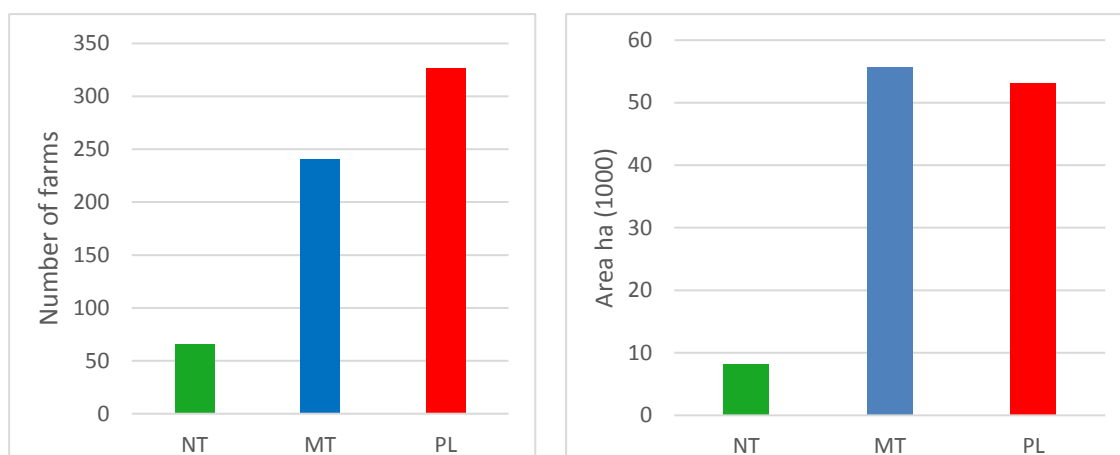


Fig. 4-1. Tillage treatments and number of farms. Fig. 4-2 Tillage treatments and farming area.

4.3.3 Factors affecting the adoption of reduced tillage in England

4.3.3.1 Farm size and reduced tillage:

The respondents are managing farms that range in size from 6.7 ha to 5,000 ha. Around 75% of the respondents were managing more than 100 ha (Fig. 4-3). The results of this survey showed that the adoption of RT increased significantly (Chi-Squared test; $P < 0.001$) with the increase in farm size (Fig. 4-4). For example, in Table 4-2, it can be observed that 97.7% of respondents who farm more than 400 ha have adopted RT, while RT is used on 31.8% of farms with less than 50 ha. On farms which are greater than 200 ha (the average farm size in England), 62.8% of the respondents have undertaken RT. The area under RT in each farm size group examined varies between 10 and 100%.

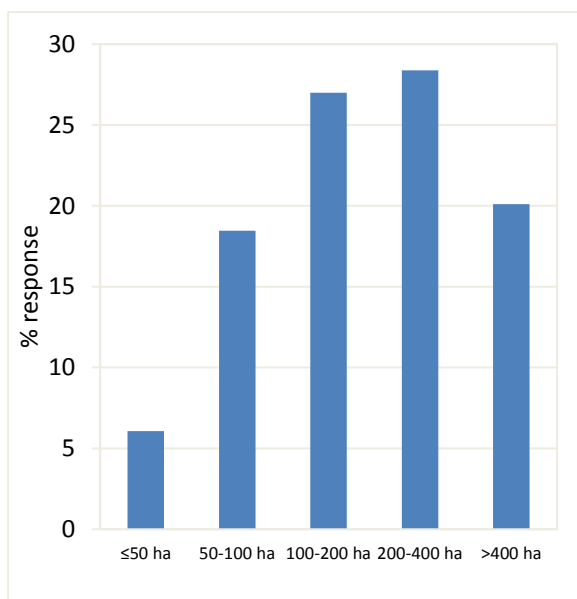


Fig. 4-3 Percentage responses according to the size of farms.

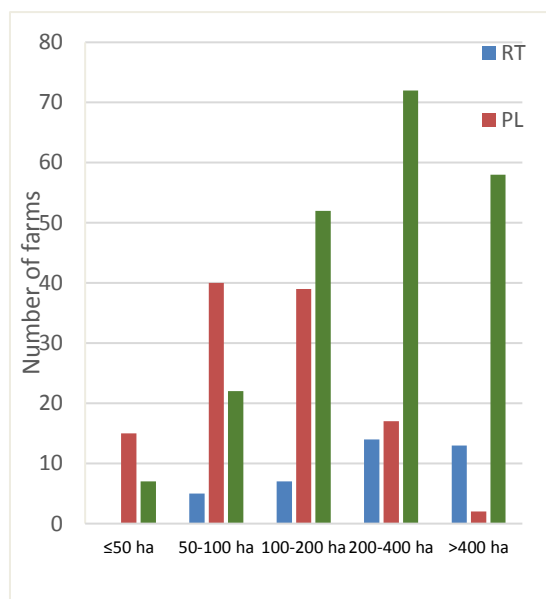


Fig. 4-4. Tillage practices according to the farm size.

4.3.3.2 Farm type and reduced tillage:

The respondents are managing different types of farms, including combinable cropping, general cropping, mixed (crops and livestock) or livestock only. However, the majority of the respondents (44.6%) are managing mixed farms of combinable crops and livestock. As a result of lower use of any form of cultivation, only 5.4% of the respondents using RT are livestock farmers (Fig. 4-5).

Farm type has a significant effect on the tillage practices used on the farm (Chi-Squared test; $P < 0.001$, Table 4-2). Farmers who manage combinable crop farms adopt RT to the greatest extent (81.9%). On general cropping and mixed farms, RT is adopted to a lower extent than on combinable crop farms, but more than observed on livestock farms where RT is only adopted on a small scale of less than (2%) (Fig. 4-6).

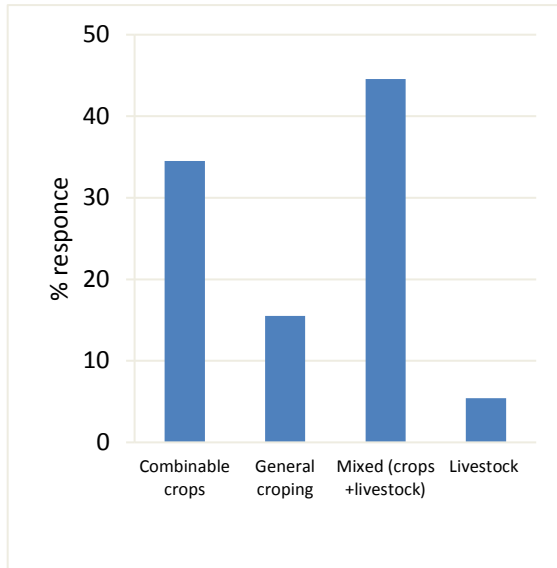


Fig. 4-5. Percentage responses according to the type of farms

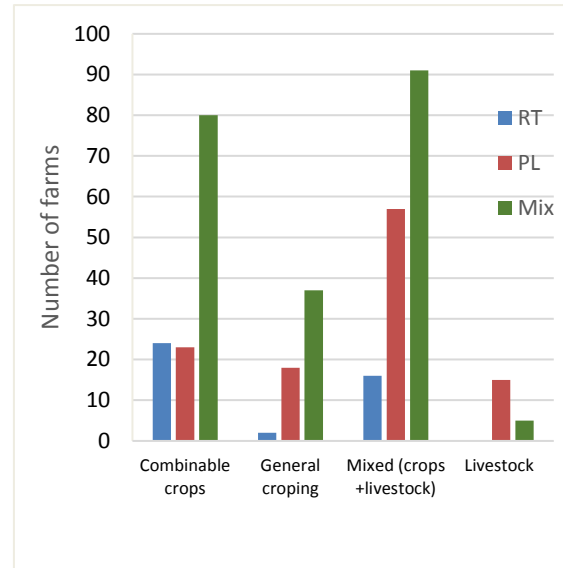


Fig. 4-6. Tillage practices according to the farm type

4.3.3.3 Government Office Regions (GOR) and European Union Super Regions:

The participants in this survey were from different areas in England. Less than one quarter (23.2%) were from East of England GOR and over one-half (51.9%) were from the wider East EU region (Fig. 4-7 and Fig. 4-8). The adoption of RT practices was not consistent across geographic regions. It varied between counties, GORs (Fig. 4-9) and the EU regions (Fig. 4-10). In East of England, South East and South West GOR, the proportion of farms using RT practices was significantly higher (Chi-Squared test; $P < 0.05$) than all other GORs (Table 4-2). Examining the EU regions, it can be seen that RT adoption was varied between the regions (Chi-Squared test; $P < 0.001$). It was highly adopted in the East (59.9%) compared to the West (17.9%) and the North (22.2%) (Fig. 4-10).

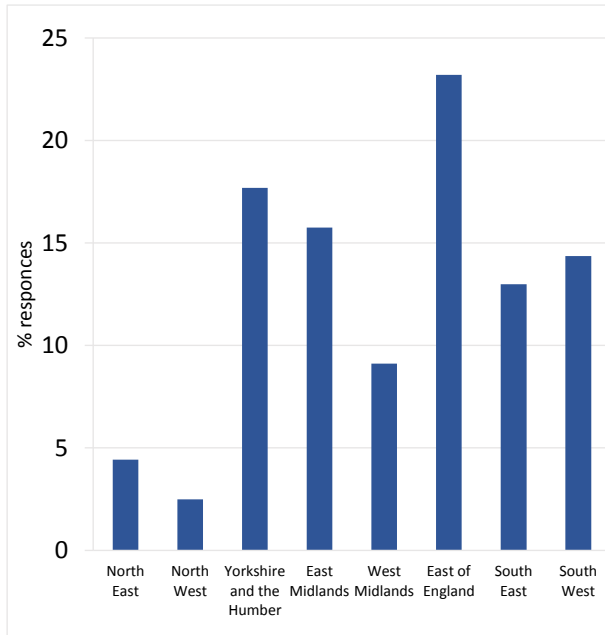


Fig. 4-7. Percentage responses according to the GOR.

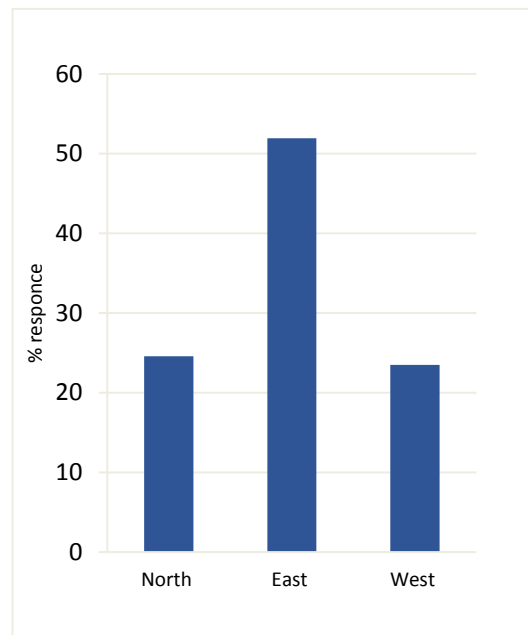


Fig. 4-8. Percentage responses according to the EU super regions.

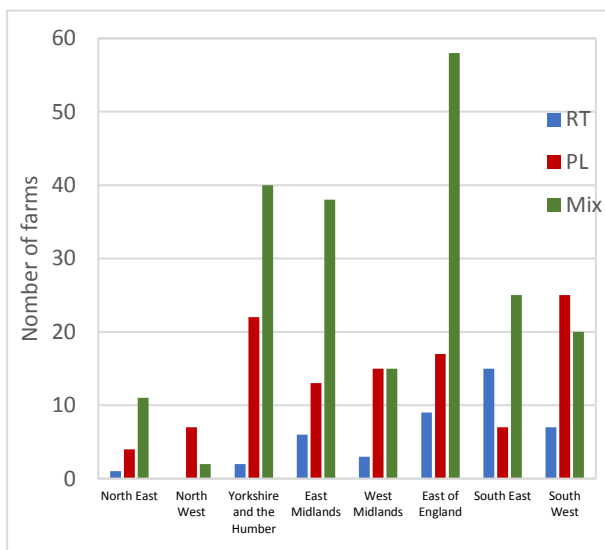


Fig. 4-9. Tillage practices according to the GOR.

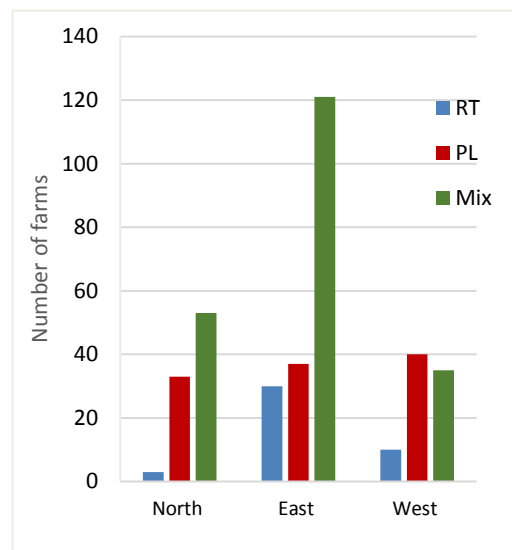


Fig. 4-10. Tillage practices according to the EU super regions.

4.3.3.4 Farmer age

The respondents in this study ranged in age from less than 25 years old to more than 75 years old; 87.43% of the respondents were 45 years or older (Fig. 4-11). The results show that farmers aged less than 45 years were more likely to adopt RT as more than 80% of this

age group were using at least one form of RT. Farmers who were more than 64 years-old were the least likely to adopt RT (60%) (Fig. 4-12). However, the difference between the age groups was not statistically significant (Chi-Squared test; $P=0.19$, Table 4-2).

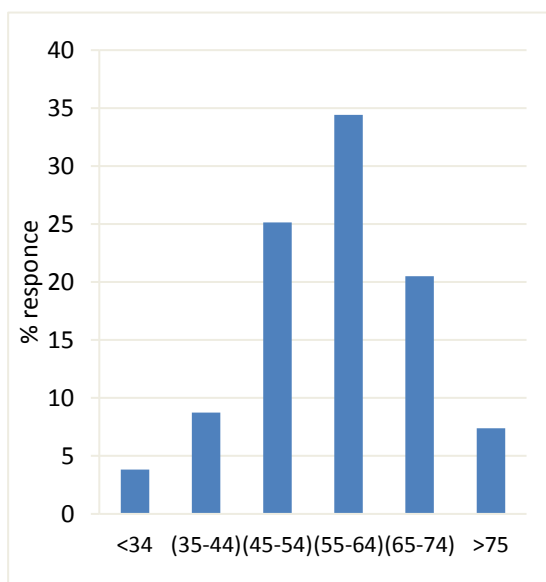


Fig. 4-11. Percentage responses according to farmers' age (years).

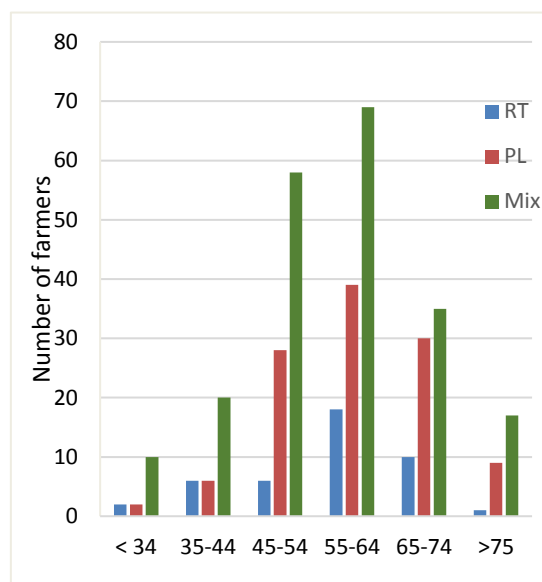


Fig. 4-12. Tillage practices according to farmers' age (years).

4.3.3.5 Education

With respect to respondent's education level, just under 80% of the respondents do not have a university degree (Fig. 4-13). The level of education significantly affected tillage practices ($P<0.001$); the adoption of RT was observed to be greater when the respondent had undertaken higher education. For example, among farmers who have at least a university degree, the adoption of RT was greater than 75%. RT was adopted by 54.23% of respondents with General Certificate of Secondary Education / A level as their highest level of academic qualification (Table 4-2).

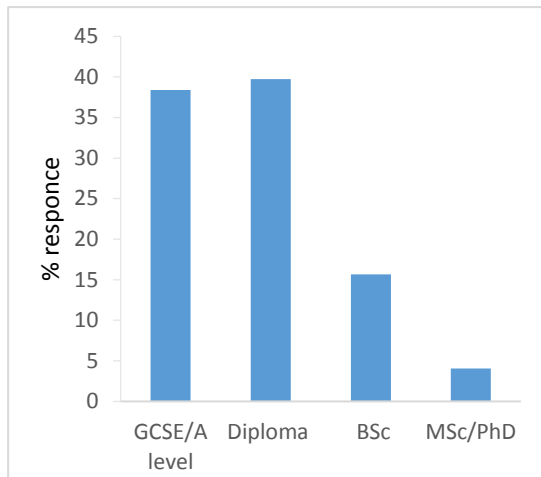


Fig. 4-13. Percentage responses according to farmers' educational qualification.

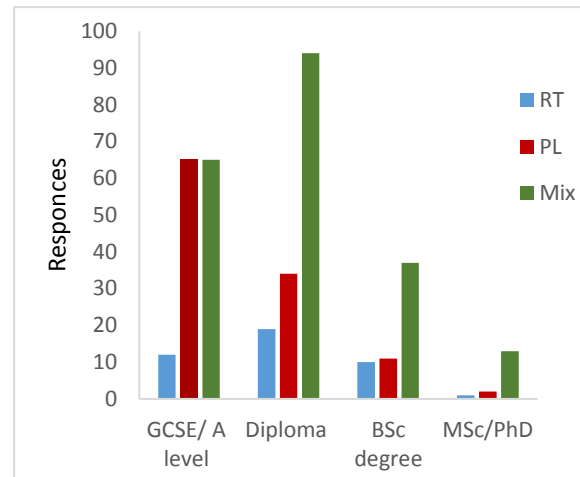


Fig. 4-14. Tillage practices according to the farmers' educational qualification.

Table 4-2. Chi-square test results showing the differences between RT adopters and non-adopters.

Variables	Options	Total number of farms (%)	Number of farms using RT compared to whole sample (%)	(%) farms using RT within the same option category	Number of farms using PL only within the same option category (%)
Farm size (ha)	≤50	22 (6.1)	7 (2.8)	31.8	15 (68.2)
	50-100	67 (18.5)	27 (10.8)	40.3	40 (59.7)
	100-200	98 (27.0)	59 (23.6)	60.2	39 (39.8)
	200-400	103 (28.4)	86 (34.4)	83.5	17 (16.5)
	>400	73 (20.1)	71 (28.4)	97.3	2 (2.7)
X²		363	250 (<i>P</i> <0.001)		
Farm type	Combinable crops	127 (34.5)	104 (40.8)	81.9	23 (18.1)
	General cropping	57 (15.5)	39 (15.3)	68.4	18 (31.6)
	Mixed (crops + livestock)	164 (44.6)	107 (42.0)	65.2	57 (34.8)
	Livestock	20 (5.4)	5 (2.0)	25.0	15 (75.0)
X²		368	255 (<i>P</i> <0.001)		
GOR	North east (1)	16 (4.4)	12 (4.8)	75.0	4 (25.0)
	North West (2)	9 (2.5)	2 (0.8)	22.2	7 (77.8)
	Yorkshire and the Humber (3)	64 (17.7)	42 (16.7)	65.6	22 (34.4)
	East midlands (4)	57 (15.8)	44 (17.5)	77.2	13 (22.8)
	West midlands (5)	33 (9.1)	18 (7.1)	54.6	15 (45.5)
	East of England (6)	84 (23.2)	67 (26.6)	79.8	17 (20.2)
	South east (8)	47 (13.0)	40 (15.9)	85.1	7 (14.9)
	South west (9)	52 (14.4)	27 (10.7)	51.9	25 (48.1)
		362	252		
X²			(6, 8, 9) <i>P</i> <0.05		
Region	North	89 (24.6)	56 (22.2)	62.9	33 (37.1)
	East	188 (51.9)	151 (59.9)	80.3	37 (19.7)
	West	85 (23.5)	45 (17.9)	52.9	40 (47.1)
X²		362	252		
			<i>P</i> <0.001		
Farmer age (year)	< 34	14 (3.8)	12 (4.8)	85.7	2 (14.3)
	35-44	32 (8.7)	26 (10.3)	81.3	6 (18.8)
	45-54	92 (25.1)	64 (25.4)	69.6	28 (30.4)
	55-64	126 (34.4)	87 (34.5)	69.1	39 (30.9)
	65-74	75 (20.5)	45 (17.9)	60.0	30 (40.0)
	>75	27 (7.7)	18 (7.1)	66.7	9 (33.3)
X²		366	252 (NS)		
Education	GCSE/A level/others (N/A)	142 (39.1)	77 (30.7)	54.2	65 (45.8)
	Diploma	147 (40.5)	113 (45.0)	76.9	34 (23.1)
	BSc	58 (16.0)	47 (18.7)	81.0	11 (19.0)
	MSc/PHD	16 (4.4)	14 (5.6)	87.5	2 (12.5)
X²		363	251 (<i>P</i> <0.001)		

4.3.4 Logistic model results

In order to identify the main farmer and farm characteristics, and drivers influencing adoption of the different tillage systems, a logistic regression was conducted. The null hypothesis of the test was that all the factors had no effect on RT adoption. The number of observations used in the descriptive statistics and chi-squared analysis was from 371 respondents. However, in the logistic regression analysis, 36 responses were excluded because of not being fully completed across all categories. A summary of the logistic regression data is provided in [Table 4-3](#).

The logistic regression model showed that farm size and farm type are significant factors influencing RT adoption ($P < 0.001$ with $df = 29$). Overall 28.5% of the variation in the model is explained by these two variables (see [Table 4-4](#)). The odds ratio (OR) is the measure of the effect of the dependent variables; farmer and farm characteristics, on the independent variable; the adoption of RT. It is used to compare between the effects of the different categories for each variable. Given a one unit change in the variable (e.g. from the reference farm type group to another farm type group), the OR shows the proportional effect of that change. Farm size has a positive impact on RT adoption. The reference farm size is 50 ha (OR=1). The OR for the category 50-100 ha is 1.22, but, this is not significantly different from the reference farm size group ($P = 0.7$). However, for the larger size farms significant differences are observed: category 100-200 ha (OR=3.35; $P = 0.05$); category 200-400 ha (OR=9.42; $P < 0.001$); category >400 ha (OR=47.04; $P < 0.001$). This means adoption of RT on farms of 50-100 ha is not significantly different than adoption of RT by farms of <50 ha. However, for farms with >100 ha, the likelihood of RT adoption is significantly greater than for farms of <50 ha.

Moreover, as farm size increases, the likelihood of RT adoption increases, and in particular with respect to the largest farm size category (>400 ha).

A further important factor in the adoption of RT was found to be farm type. The reference group (OR=1) was combinable crop farms. Mixed farms return an OR of 0.399 ($P=0.015$); general cropping farms have an OR of 0.38 ($P=0.05$), and livestock farms have an OR of 0.09 ($P=0.005$). Thus, the OR values show that RT is more likely to be adopted on combinable crop farms, as the OR for the other farm types is less than one in each case and significantly different from the reference group. In this logistic regression model, the remaining variables - gender, age, GOR, education, were found not to have a significant impact on adoption of RT.

It is informative to note that there is a correlation between farm size and the education level of the farmer. As farm size increases, the percentage of respondents with higher level educational qualifications also increases. In [Table 4-4](#), it can be seen that 41.67% of respondents who have achieved masters (MSc) are farming between 200- 400 ha and a further 41.67% of respondents with the same degree are managing more than 400 ha farms. By contrast, 6.02% of the respondents who achieved GCSE/A-levels as their highest educational qualification are managing more than 400 ha. Examining farm locations, it can be seen that the respondents who operate large farms are more likely to be located in the East England EU region. So, level of education and location may be important but masked by farm size.

Neither farmer age nor years of experience have a significant effect on RT uptake. The reference age group was “less than 34-year-old” (OR=1). The age category 35-44 was observed to have the greatest likelihood of RT adoption (OR=1.16; $P=0.9$), with the least

likely being the 65-74-year-old group (OR=0.38; $P=0.43$). As anticipated, given the link between age and experience, farmer experience did not show a significant impact on RT uptake. The OR for farmers with 20-30 and 30-40 years of experience, were, respectively 1.38 and 1.25, but these were not significantly different from the reference group (less than 10-year experience).

Table 4-3. Summary of the logit regression data.

Variables	Observation	Mean	Standard Deviation	Minimum	Maximum
Reduce tillage	334	69.46	46.13	0.00	100.00
Farm size	334	3.39	1.18	1.00	5.00
GOR	334	5.43	2.32	1.00	9.00
Farm type	334	2.18	0.98	1.00	4.00
Farm tenure	334	2.00	0.94	1.00	3.00
Age (year)	334	58.08	12.00	30.00	80.00
Minimum experience (year)	334	24.73	11.54	5.00	40.00
Gender	334	0.97	0.16	0.00	1.00
Highest education level	334	1.85	0.85	1.00	5.00

LR Chi-Squared (29) = 116.84, Chi Squared test $P<0.001$, Log likelihood = - 6.38, Pseudo $R^2 = 0.29$

4.3.5 Assessment of the model

In this model, Nagelkerke R^2 value is 0.42. It should be noted that with logistic regressions, R^2 is less likely to reach the value of 1 due to using the odds ratio as the basis of calculation (Cohen et al., 2013), consequently, the value of 0.42 represents a good model fit. In this study, the Wald test indicates that the farm size and the farm type variables are significant ($P<0.05$, Table 4-5). As the likelihood ratio (LR) test value is less than 0.05 (a significant result indicates poor prediction) the null hypothesis is rejected and the model does fit the data (Engle, 1984, Agresti, 2002, Bewick et al., 2005).

Table 4-4. The percentage of respondents within groups by farm size categories.

Variables		Farm size less than 50 ha %	Farm size (50- 100) ha %	Farm size (100-200) ha %	Farm size (200-400) ha %	Farm size more than 400 ha %
Tillage	RT adopter	3.45	9.91	24.14	34.05	28.45
	Non-RT adopter	13.73	34.31	34.31	15.69	1.96
Region	East England	8.67	13.87	21.39	28.32	27.75
	North England	2.44	19.51	36.59	29.27	12.20
	West England	6.33	22.78	30.38	27.85	12.66
GOR	North east (1)	0.00	20.00	40.00	26.67	13.33
	North West (2)	11.11	22.22	33.33	33.33	0.00
	Yorkshire and the Humber (3)	1.72	18.97	36.21	29.31	13.79
	East midlands (4)	11.11	16.67	25.93	27.78	18.52
	West midlands (5)	3.45	13.79	37.93	34.48	10.34
	East of England (6)	8.97	14.10	19.23	24.36	33.33
	South east (8)	4.88	9.76	19.51	36.59	29.27
	South west (9)	8.00	28.00	26.00	24.00	14.00
	Combinable crops	9.92	16.53	20.66	29.75	23.14
	General cropping	6.12	14.29	28.57	16.33	34.69
Farm type	Mixed (crops and livestock)	2.70	16.89	31.76	33.11	15.54
	Livestock	18.75	37.50	31.25	12.50	0.00
Farm tenure	Own all land	10.96	24.66	23.97	23.97	16.44
	Tenant	4.76	11.90	38.10	28.57	16.67
	Mixed	2.74	11.64	27.40	32.88	25.34
Age (years)	< 34	0.00	0.00	30.77	23.08	46.15
	35-44	0.00	12.90	16.13	38.71	32.26
	45-54	1.22	13.41	32.93	28.05	24.39
	55-64	7.02	19.30	28.07	25.44	20.18
	65-74	17.39	15.94	17.39	36.23	13.04
	>75	4.00	40.00	44.00	12.00	0.00
	< 10	0.00	0.00	29.17	29.17	41.67
Experience (years)	10-20	1.85	11.11	31.48	33.33	22.22
	20-30	4.49	15.73	29.21	26.97	23.60
	30-40	5.81	18.60	18.60	38.37	18.60
	>40	14.81	27.16	30.86	16.05	11.11
	Male	6.46	16.92	27.08	28.62	20.92
Gender	Female	11.11	33.33	33.33	22.22	0.00
	GCSE A level/no education	8.27	27.07	30.83	27.82	6.02
Education	Diploma	7.41	10.37	27.41	24.44	30.37
	BSc degree	1.92	11.54	23.08	36.54	26.92
	MSc	0.00	8.33	8.33	41.67	41.67
	PhD	0.00	50.00	0.00	50.00	0.00

Table 4-5. The effects of different variables on the reduced tillage adoption using the odds ratio.

Variables		Odds Ratio	Std. Err.	Wald /z/	P value	[95% Confidence Interval]
Farm size	≤50 ha	1.00				
	50-100 ha	1.22	0.74	0.33	0.74	0.37, 4.03
	100-200 ha	3.35	2.04	1.99	0.05	1.02, 11.02
	200-400 ha	9.42	5.98	3.53	0.00	2.71, 32.71
	>400 ha	47.04	43.67	4.15	0.00	7.63, 290.17
Region	East England	1				
	North England	0.76	0.63	-0.33	0.75	0.15, 3.89
	West England	0.54	0.33	-1.01	0.32	0.16, 1.79
GOR	North east (1)	1.00				
	North West (2)	0.24	0.27	-1.24	0.22	0.024, 2.32
	Yorkshire and the Humber (3)	0.69	0.52	-0.5	0.62	0.16, 2.998
	East midlands (4)	1.34	0.83	0.47	0.642	0.4, 4.5
	West midlands (5)	0.87	0.52	-0.23	0.82	0.27, 2.84
	East of England (6)	0.85	0.5	-0.27	0.78	0.27, 2.71
	South east (8)	-	-	-	-	-
	South west (9)	-	-	-	-	-
Tenure	Own all land	1				
	Tenant	1.06	0.5	0.12	0.91	0.42, 2.67
	Mixed	1.77	0.61	1.65	0.1	0.9, 3.5
Age (years)	< 34	1				
	35-44	1.16	1.36	0.13	0.9	0.12, 11.46
	45-54	0.44	0.49	-0.74	0.46	0.052, 3.8
	55-64	0.59	0.67	-0.47	0.64	0.06, 5.54
	65-74	0.38	0.46	-0.8	0.43	0.036, 4.05
	>75	1.07	1.39	0.05	0.96	0.08, 13.57
Experience	Less than 10	1				
	10 years	0.7	0.58	-0.43	0.66	0.14, 3.54
	20 years	1.38	1.16	0.39	0.7	0.28, 7.14
	30 years	1.25	1.13	0.25	0.8	0.22, 7.29
	40 years	1.04	1.01	0.04	0.97	0.16, 6.94
Gender	Female	1				
	Male	1.02	0.82	0.03	0.98	0.21, 4.98
Education	GCSE A level or equivalent / no education	1				
	Diploma	1.34	0.46	0.85	0.4	0.68, 2.64
	BSc degree	1.74	0.9	1.08	0.28	0.63, 4.79
	MSc	1.36	1.36	0.31	0.76	0.19, 9.63
	PhD	-	-	-	-	-
Farm type	Combinable crops	1				
	General cropping	0.39	0.19	-1.93	0.05	0.15, 1.02
	Mixed (crops and livestock)	0.40	0.15	-2.43	0.02	0.191, 0.84
	Livestock	0.09	0.0799	-2.79	0.01	0.018, 0.496

4.3.6 Factors that encourage farmers to keep ploughing

In addition to the farm and farmer characteristics that influence RT uptake, respondents cited a range of reasons for not undertaking RT with respect to soil type and weed management (Table 4-6). Prominent soil type had a substantial influence among the respondents, with 72.25% noting that their decision to plough or to follow a RT system, was dependent on soil type. Some respondents mentioned that soil type varied across the farm and consequentially it was not suitable to have a RT system on the whole farm. In a wet year, respondents mentioned that they tend to plough heavy clay soil to help in drainage and to prevent water from forming pools on the surface.

Weed management was cited as the second most challenging factor with respect to RT uptake in the long term. Nearly two-thirds (62.78%) of the respondents noted that weed management was a factor in the decision making with respect to ploughing and RT. The third most cited reason noted was the weather, with respondents tending to plough intensively in wet years, aiming to help soil drainage and to avoid water erosion.

Table 4-6. Factors influencing farmers' decision whether to plough or not.

Variables	Not important at all/not important/NA	Neutral	Important/Very important
Prominent soil type	0.97	16.75	72.25
Weeds	25.97	36.25	62.78
Weather	61.65	23.05	50.97
Labour availability	30.94	33.53	44.12
Soil organic matter	26.14	40.72	42.51
Water availability	19.08	39.31	41.62
Machine availability	22.35	35.80	38.07
Crop varieties	10.99	38.67	30.39
Soil nutrients	23.84	54.07	22.09
Climate change	16.77	29.32	9.02

4.3.7 Barriers to the adoption of RT

Before asking farmers about challenges they face in undertaking any of the RT forms, they were asked whether they have attempted any of them. This was to understand whether their answers were based on their personal experience. Of the 371 respondents, 167 have not tried or used NT and 61 have tried it but did not carry on this practice. In the same sample (371), 77 of the respondents have not used or tried MT and 59 have tried it but did not keep using it (Table 4-7). However, respondents have mentioned several difficulties which are presented below.

Table 4-7. Numbers of farmers who have tried or used RT practices compared to the RT adopters.

RT systems	Using	Tried	Not using or tried
NT	38	61	167
MT	165	59	77

4.3.8 The challenges of undertaking MT (RT excluding NT)

Fig. 4-15 presents the challenges of practising MT. It can be seen that weed burden is the main challenge, cited by 134 respondents. Slugs were the second most cited challenge from 88 respondents. Other challenges included untidy fields, poor crop establishment, lower yields and more crop diseases, however these factors were cited less frequently than those relating to weeds and slugs. Respondents were invited to cite other challenges as an open question; these are listed in Table 4-8. Quotes from respondents are provided to indicate the challenges cited.

4.3.9 The challenges of undertaking NT (RT excluding MT)

Respondents who have practiced NT were also asked to cite challenges from practising this system. Following the pattern observed for MT, the most common problems mentioned by 79 of the respondents was the increase in the population of the slugs and then weed control (78 respondents). Poor crop establishment was listed as the third

common problem, followed by top soil compaction. It is noticeable that the difference between the responses was not as large as those observed for MT challenges (Fig. 4-16). Respondents added further comments on this question, as shown in Table 4-9.

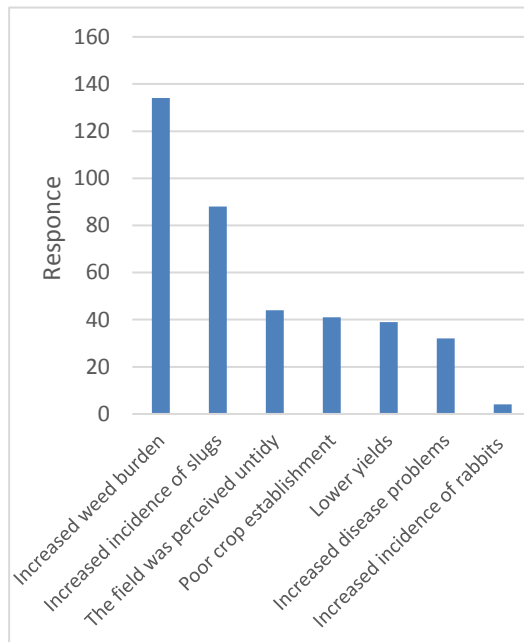


Fig. 4-15. Farmers' responses regarding to the challenges of minimum tillage practice.

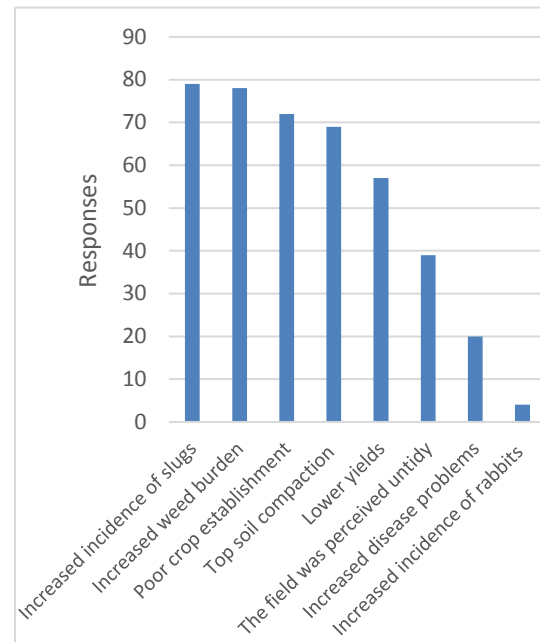


Fig. 4-16. Farmers' responses regarding to the challenges of no-tillage practice.

Table 4-8. Additional comments respondents mentioned for not adopting MT.

Typical comments summarised	Quotes
Drill blockages	• “Drill blocking with crop residues, drill clogged up with trash. • “Finding a drill to cope with the trash. We tried Moore and then found a Claydon able to cope”. • “Problem of surface trash when weather turns wet =>drill blockages” • “Higher amount of crop residue collecting up and blocking under the coulter of drill”
Weeds problem	• “Grass weeds could be a problem, but establishment was much better “ • “Black grass” • “Volunteers” • “Increase in weeds when first tried but no possible less” • “Grass weeds”
Yield and crop establishment	• “Lower yield for a start” • “Lower yield and crop diseases depend on season. Crop establishment depends on weather.”
Soil compaction	• “Soil compaction and incorporation of Farm Yard Manure (FYM) difficult (or less effective)”
Wet weather	• “Poor drainage” • “wet conditions” • “Once cultivated field has to be drilled before it gets too wet” • “Can’t do it in a wet year (weather)” • “No real problem encountered unless heavily land cultivated and does not have time to weather before drilling”
Chemical substances	• “Less nitrogen mineralised during autumn”. • “Chemicals are not working as well”. • “Increased chemical costs”

Table 4-9. Additional comments respondents mentioned for not adopting NT.

Typical comments summarised	Quotes
Soil compaction	• “Sub soil compaction, this is a heavy clay soil (Keuper marl)” • “Compaction: depends on weather” • “No crop at all in some parts of the field” • “Impossible to incorporate manure as required by cross compliance” • “Compaction because of ever bigger machinery trailers etc.”
Soil type	• “Our soil type is not very good for No-tillage”
Does not work in crops such as	• “With sugar beet in the rotation, ploughing is always needed.” • “Mainly used for OSR establishment. Can sometime fail due to dry weather and slugs”. • “OSR only, no problems”
Field	• “Uneven field” • “Land is not suitable” • “Don’t have enough hectares for 2 systems.”
Weed management	• “Grass regrowth in Kale. Black grass” • “black grass” • “Suffer from weeds in the grass” • “Sterile brome areas” • “Chemical bill” • “Increased Pigeon damage on OSR.”
Winter or Spring crops	• “OK in autumn. No good for spring crops yet! Heavy clay soil” • “Fields are wetter and colder in Spring”
Organic farm	• “Organic. Organic farmer issues with potential pest/weed competition”
Driller, residue problems	• “Drill clogged up with trash” • “Learning to deal with residues” • “Drill clogging np”
Contractors	• “No contractor with direct drill”
Machinery	• “Cannot afford machinery required” • “Prohibitive cost of equipment for small farm” • “But advantage is better for machinery to travel on in subsequent operations”
Weather conditions	• “Wet conditions” • “Plant, drainage, water logging, weather”
Water drainage	• “Poor water drainage, headlands can yield lower all because of all the trashes- combine bailer, trailers” • “Poor drainage”

4.4 Discussion

The area estimated to be cultivated under reduced tillage (RT) typically varies between studies. The results of the present study estimate that 54.56% of the land in England is cultivated under RT (47.61% under MT and 7.04% under NT). By contrast, the area under RT was estimated by Defra (2010) as 44%, with a lower estimate of 32% presented in a recent study by Townsend et al. (2016) who argued that Defra's estimate was based on farmer responses biased towards those interested in RT, and that this may have led to an upward bias in the area estimated to be under RT practices. The bias is possible in all studies of this kind, including the present one, but having a large number of respondents who are not undertaking RT on their farms and some of them have declared that they are not planning to change their current tillage policies indicates that this study is less likely to be biased. Our results show that more farms are undertaking RT compared to Townsend et al. (2016). This could be attributed to the recent increase in fuel price which might be encouraging farmers to uptake RT.

Our results demonstrate that many respondents do not undertake only one form of tillage technique, confirming findings from previous studies e.g. Townsend et al. (2016) which noted that farmers did not accept the dichotomy concept of tillage practice. Farmers who are interested in RT also tend to plough at specific times before or after certain crops; this being defined as rotational ploughing which is observed to be more frequently practised than strategic ploughing. This study supports the results of the 2010 *Survey on Agricultural Production Methods (SAPM)* in Europe (EuroStat, 2013) and those of Townsend et al. (2016) in England which concluded that RT is more frequently

adopted on larger farms. There is a positive relationship between farm size and RT uptake which could be attributed to a range of reasons:

1. It is expected that large farms would be able to provide the funding required to buy the machines needed for RT assuming that farmers already own traditional ploughs.
2. It is more feasible for large farms to own or have access to a larger range of machines than for smaller farms - hence large farms can own both machines for RT and ploughing, whereas small farms are less likely to have the financial ability to hold a range of tillage machines at the same time.
3. To some extent RT adoption is still in the experimentation phase for many farmers. Consequently, managers of large farms are more likely to have the ability to take the risk of trying new practices on their farms. Managers of small farms may not be willing or able to bear the potential reduction in yield in the first one or two years of the transition to RT, and they may not have the ability to overcome any loss, whereas managers of larger farms may be better able to compensate losses from other crops ([Lahmar, 2010](#)).
4. Timeliness is an important factor which is more crucial on large farms ([Melander et al., 2013](#)). Time required for crop establishment can be reduced using RT practices. Consequently, farmers could complete the field preparation in a relatively shorter time compared to PL ([Carter et al., 2003a](#)). UK farmers have a narrow window before seedbed establishment for the next winter crops, thus maximising timeliness for cultivation has a crucial importance to optimise crop yield ([Morris et al., 2010](#)).

Supporting the previous literature on RT adoption, our results show that RT is adopted predominantly on combinable crop farms compared to general cropping and mixed crop farms. This is argued to flow from the diversity of the crops grown on one farm. Different crops have different tillage and drilling requirements ([Bossange et al., 2016](#)). This creates a burden on farmers to spend more money owning the range of required machines and also more time to learn the best practice for every crop. Another reason could be the funding required for different soil preparation machines, as farmers seek to minimise expenditure.

It has been previously observed that there is greater potential of RT uptake in the East of England region ([Cannell, 1985](#)). Our results confirmed that RT is now relatively popular with farmers in that region, but it is not an independent influencing factor. Two main factors associated with greater RT uptake were large farm size and combinable cropping activities; the region within which the farm is located was not, in itself, identified as a significant driver of RT uptake although farms in the East of England tend to be larger than other regions.

In support of [Morris et al. \(2010\)](#), respondents in our study noted the problems of weeds and unsuitable soil types as barriers to the uptake of RT. Farmers respond to these two main problems using rotational ([Powelson et al., 2012](#)) and strategic tillage ([Townsend et al., 2016](#)) strategies. The need to maintain strategic and rotational tillage practices that include deep ploughing may, in part, be responsible for the different estimation of RT uptake observed between different studies.

RT machines are attractive for farmers with respect to use high technology machines, but these high cost machines may not be afforded by many farmers. Managers of large

farms are likely to more promptly take on technologies as they are able to spread the cost over a greater land area. Whereas spending the same investment would need more consideration from small farmers and consequently expensive cutting-edge technologies take more time to become established on smaller farms. For instance, in the United States, high cost machines were considered a barrier to RT uptake ([Lambert et al., 2012](#)). By contrast, the adoption of the low cost innovation such as improved seed is much quicker ([Krause and Black, 1995](#), [Swinton et al., 2015](#)).

The results of the current study are based on a postal approach. This method has been criticised in the past by [Pennings et al. \(2002\)](#) who argued that only people who were interested in the subject would respond. In our study, this approach was used to reach a large number of farmers across England at a suitable time of year aiming to encourage response. Recognising the challenge of response bias, attempting to encourage farmers who were not interested in RT to reply, the covering letter clearly stated that the survey was to explore tillage practices in general. Structurally, within the questionnaire, respondents who undertook deep tillage only were directed to specific pages of the questionnaire. This might have encouraged farmers who are in opposition to RT to participate.

Getting farmer addresses from a commercial company has been criticised by [Morris et al. \(2010\)](#) and [Lobley and Butler \(2010\)](#) who believed that contacting farmers through this way bias the questionnaire towards larger farms. However, the results of this study did not agree with both studies as the questionnaire was completed by a high proportion of farmer irrespective of farm size as cultivation is an area of concern for all

farmers. Furthermore, almost equal number of farmers from each farm area category completed the survey.

The process of adoption used by current RT practitioners

RT is practised on many farms because of time and economic reasons and to a lesser extent because of soil maintaining and the environmental benefits. Agricultural innovation in general means using new technology which changes the production positively, however, a level of uncertainty is embodied in this process. When farmers become well informed about the technology, the uncertainty diminishes. Thus, the analysis of the agricultural adoption is a dynamic process that requires continuous update and observation ([Feder and Umali, 1993](#)). The attitude of English farmers towards RT practices as an innovation seems to entitle large uncertainty. To overcome this uncertainty, farmers need to get further access to the relevant information and experience. In conjunction with that, it is suggested that each farmer needs to make their own changes that suit the conditions on their farms ([Coughenour and Chamala, 2007](#)). Thus, further farm innovation may facilitate the spread of RT.

The adoption scenario of RT could be similar in different parts of the world. In California for example, it is thought that there are two paths. The first one is when farmers are informed about RT from other farmers, then they experience it; if they are convinced about the results, they will adopt those practices gradually “trial and error”. The second path is when farmers know about RT but they do not adopt it due to a number of barriers. However, they will fully adopt it when they get to a point where they know how to overcome those barriers and can guarantee the successfully application. Both of these scenarios indicate that an essential part of this process is to know how, and to

what extent, farmers are informed about RT (Bossange et al., 2016). To this end, it is believed that farmers need to be provided with more knowledge about RT this experimenting phase of RT uptake (Uri, 2000). This could be through encouraging farmers to have a location for trials as it will allow them to see the result before full adoption.

4.5 Conclusion and policy recommendation

Previous research on the adoption of RT has largely focused on the environmental, financial and agronomic advantages. By contrast, this chapter has presented an overview on RT adoption status and attempted to explore the effects of farm and farmers' characteristics on the uptake of different tillage techniques, including capturing data on challenges that farmers' have observed from their uptake of RT. Farmers' empirical experiences with different crops and using different tillage strategies have been demonstrated.

This study concluded that farm size and farm type are the main factors affecting the uptake of RT on farms in England. Small farms are the least likely adopters of RT, but it is the most adopted in large, combinable crop farms. Farmer personal characteristics were not found to be main drivers of RT adoption and climate change mitigation via reducing GHG emissions was not identified as being a main reason for farmers adopting RT.

Prominent soil type is the main driver for which tillage system to undertake on a farm. Weed management and slugs were identified as main challenges for RT adopters. More improved herbicides are needed and a legislation change for farmers to use more

effective chemicals is required ([Melander et al., 2013](#)). Long rotations on the same farm could be a method for reducing tillage frequency and combating weeds as crop rotations prevent the build-up of the pathogens and pests when one crop is grown frequently ([Townsend et al., 2016](#)). Strategic and rotational ploughing were observed to overcome these constraints, but this would reduce the climate change mitigation potential of RT.

To enable the transition from PL to RT practices on farms with smaller land areas, more agricultural extension is required; equally, gaining access to RT machinery at reasonable cost will be an important consideration. As the cost of machines required for RT was mentioned as constraint, long term loans and/or financial governmental support are suggested in order to enable smaller farmers to purchase those machines. As RT is less undertaken in farms where cereals are not the main crops; such as vegetable and root crop farms, it is recommended that more research and experimental work be conducted to explore the effects of RT on growth and yield of these crops.

RT adoption is a dynamic and a multi-faceted process that requires information and demonstration. For this reason, having benchmark fields where farmers can see the results of the different tillage practices could assist in spreading this knowledge. Knowledge exchange is highly important between researchers and farmers. This may allow scientists to find solutions for the problems of weeds and compaction if found in RT fields, such as improving resistant crop varieties or growing certain crops. More active field visits to experiments and fields where NT has been successfully undertaken are recommended, as successful stories of innovative farmers can encourage other farmers ([Ghadim and Pannell, 1999](#)); hence better communication between researchers and farmers seems to be necessitated. With the rapid increase in social media channels,

it could be an effective way to contact farmers and influence their decisions. Overall, these recommendations may assist to minimise any uncertainty farmers may have towards RT and assist in the mind-set change suggested for a better RT undertaking.

Future work should seek to analyse the different factors constraining RT uptake and examine the soil-based environmental aspects of RT, in particular short-term impacts, highlighting the importance of NT and other RT practices to accumulate organic matter in the soil layers and mitigate climate change.

The postal questionnaire method undertaken in this study seems an effective way to reach a large number of farmers. For future work, interlinking this method with interviews of respondents willing to talk more about their experiences is recommended to collect in depth information about farmers' individual experiences.

5 Chapter 5: General discussion and conclusions

5.1 Benefits of reduced tillage and residue retention

5.1.1 Yield

There are conflicting reports from the literature regarding the crop yield under Conservation Agriculture e.g. [Knight \(2004\)](#), [Verch et al. \(2009\)](#), [Van den Putte et al. \(2010\)](#) and [Arvidsson et al. \(2014\)](#). Overall, yields from plough-based tillage systems do not exceed yields from CA systems once CA yields have stabilised ([FAO, 2004](#)). Time for yield stabilisation varies among the regions according to different reasons including soil type and weather conditions ([Mangalassery et al., 2015](#)).

In the first year of the field experiment, no differences in yield were detected between the different tillage treatments. But in the second year, NT caused a 10% reduction in the triticale yield compared to PL and MT. It is most likely that soil compaction was exacerbated by the unusual weather conditions (heavy rain late in June 2016) negatively affecting yield. This kind of yield reduction has been previously reported in a limited number of previous studies such as [Van den Putte et al. \(2010\)](#) and [Arvidsson et al. \(2014\)](#). In contrast, [Knight \(2004\)](#) and [Verch et al. \(2009\)](#) observed increased crop yields under NT. It is expected that when the system is stabilised, it will protect (buffer) the crop from extreme weather conditions. Before judging whether NT practices are preferably to more commonly adopted tillage techniques, it is informative to note that the adoption of CA has been theoretically divided into four phases: 1) improving the tillage techniques, 2) improving the soil conditions and fertility, 3) diversification of cropping pattern and 4) at this stage, the farming system should be functioning smoothly, with crop yield stabilised ([FAO, 2004](#)). Before the fourth stage, the technical

and economic advantages of CA cannot be directly observed, and thus not fully appreciated by farmers. Overall, in our research experiment, achieving equivalent yield and slightly lower yield from NT compared to ploughing, can arguably be considered to provide a positive relative yield outcome, as the experimental basis relates only to the first phase identified above, before the expected soil improvement occurs.

Applying conservation agriculture as a package instead of individual parts

The yield variation could be reduced or even avoided if the three CA principles were applied simultaneously, in contrast to application of a single CA principle alone. [Pittelkow et al. \(2015a\)](#) found that the negative effects of NT were highest when NT was applied alone and the negative effects were minimised when other CA principles were undertaken. While these recommendations have been emphasised in sub-Saharan Africa or South Asia ([Erenstein et al., 2012](#), [Corbeels et al., 2014](#), [Stevenson et al., 2014](#)), within a UK context, it is argued that the promotion of NT should be accompanied with appropriate residue retention and crop rotations ([Basch et al., 2012](#)).

5.1.2 The financial benefits

Undertaking RT and residue retention, as part of the CA system, has many environmental benefits such as reducing soil erosion, runoff of pesticides and fertilisers, watercourse sedimentation, nutrient leaching and GHG emissions ([Fawcett and Towery, 2003](#), [Holland, 2004](#), [Morris et al., 2010](#)). In temperate humid areas such as UK and Northern Europe, soil erosion and water shortage are less of a problem than semi arid areas, but remain an important issue in most regions ([Davies and Finney, 2002b](#)). However, it is proved that RT and residue retention have potential financial benefits

which are of direct importance to farmers ([Šarauskis et al., 2014](#)). RT requires lower machinery use reduces costs ([Knight, 2004](#), [Vozka, 2007](#), [Godwin, 2014](#)). This might be the primary motive for farmers to take up RT ([Davies and Finney, 2002b](#)) in conjunction with improved timeliness ([Morris et al., 2010](#)). These financial benefits can reach approximately €100 ha⁻¹ as a net return in comparison to PL systems ([Verch et al., 2009](#)). This estimation was in field experiment following crop rotation: winter rape (*Brassica napus* L.) – winter wheat (*Triticum aestivum* L.) – maize (*Zea mays* L.) – winter wheat – winter barley (*Hordeum vulgare* L.). This benefits will increase the farm gross margin, provided yield is maintained.

These financial benefits may be less viable if the crop yield is not maintained. To maintain crop yields, additional costs may be required for supplementary herbicides, pesticides, chemical and biological plant disease control. Farmers increase the usage of these substances when increased weed population, fungi and/or pests are predicted. This might be exacerbated in years when the weather conditions favour weeds and pests ([Melander et al., 2013](#)). If crop residues are retained, then further application with fungicides and molluscicide may be required ([Soane et al., 2012](#), [Bürger et al., 2012](#)). However, reduced tillage cost models show that reduction in fuel costs outweigh the cost increase caused by using extra chemicals ([Lafond et al., 1993](#), [Nail et al., 2007](#)).

Previous work has shown that additional cost might be needed for nutrients when NT is undertaken. Nutrients such as nitrogen (N), phosphorus (P), and sulfur (S) are required for biomass materials (e.g. crop residues) to be transformed into SOC. Increased amounts of nutrients would be needed if the crop residues are retained, so that the C: nutrient ratio can be kept balanced. Most cereal crop residues have a wide ratio of C:N (100), C:P

(200), and C:S (500) compared to that of SOC at 12, 50, and 70, respectively. Assuming that the humification efficiency is around 40%, [Himes \(1997\)](#) found that sequestration of ten tonnes of biomass C as SOC requires 62 tonne of oven dry residues consisting of 28 tonnes of C and 0.83 tonne of N, 0.2 tonne of P, and 0.14 tonne of S. This will produce 17.24 tonnes of humus. Similarly, [Richardson et al. \(2014\)](#) found that increasing SOC by 1 Mg C ha⁻¹ into humus requires 73, 17, and 11 kg ha⁻¹ of N, P and S, respectively. Thus, both SOC and crop production require nutrients, for this reasons, [Lal \(2014\)](#) suggested that the concept of “fertilising the system” should be presented instead of using the term “fertilising the crop”. This is to include the hidden cost of the nutrients required for the humification and SOC production.

Managing changes in input use

As part of the farm management, comparing the inputs required for CA practices and conventional agriculture indicate that these do not differ very much. However, the differences can be summarised in a few points. First, seed use is likely to remain the same under both tillage regimes. A related point to consider is that under CA, the seeding rate and plant density are optimal as the seeds distribution is expected to be well organised in a homogeneous soil structure across the field. Second, plant residue retention is an essential part of CA, but residues can be replaced with cover crops. In this case, farmers would have to buy cover crop seeds if they are not produced on the same farm. Third, at the early stages of CA uptake, farmers need to continue adding the same amount of herbicides as in conventional tillage. This should not make any difference to farm income. However, over time, the expenditure on herbicides should reduce as the organic soil cover is expected to suppress the weeds and consequently

fewer herbicides will be needed. Knife rollers can be used on organic farms and when farmers are able to afford money to buy them. This might help organic farmers, as combating weed is their main challenge when replacing ploughing with NT. It is informative to mention that crop rotation as part of CA, would be an eco-friendly way to mitigate weeds and pests. Overall, this will help to reduce production costs in the longer term ([FAO, 2004](#), [FAO, 2018](#)).

By taking up CA, farmers would be able to reduce labour use, depending on outsourced skilled workers and contractors, to achieve larger work outputs over a shorter time. This might be more important in places where trained agricultural workers are not affordable or in short supply. This latter point is considered to be one of the main motivations for the widespread adoption of CA in South America in addition to retention of natural resources ([Kassam et al., 2014](#)).

Machinery and Equipment

Using CA is associated with lower use of machinery and field equipment compared to traditional ploughing. For instance, CA operations do not require plough and harrows, reducing fuel and labour costs ([Lafond et al., 1993](#), [Nail et al., 2007](#)). While high powered tractors are needed for ploughing, low powered ones are used for CA two main operations; direct drilling and spraying. Similarly, in CA there will be less wear and tear of the machines. Consequently, money for repair and maintenance will be minimised.

Farmers in some part of the UK can get support to buy NT machines. There is currently EU funding available through a scheme called LEADER which provides 40% of the cost towards NT machinery as a practice reducing impacts on soil and greenhouse gases. Applications can be made by farmers, growers, foresters, other local rural businesses

and rural community organisations who are in the North and West Northamptonshire Local Action Group (LAG). But, not all of the UK rural areas are covered by a LAG, consequently they cannot apply for this programme (Kelly, 2015).

5.1.3 Climate smart agriculture

CA is a step towards climate smart agriculture (Neufeldt et al., 2013, Harvey et al., 2014). This will be achieved through its advantages in increasing soil carbon sequestration, reducing GHG emissions consequently mitigating climate change. Each of these points is discussed separately below:

A) Soil organic carbon (SOC) and ecosystem functions

Increasing SOC is a promising way to mitigate climate change and reduce GHG emissions. Also, SOC is believed to maintain soil physical, chemical and biological properties all of which help in improving crop growth and yield with higher importance in depleted soil (Lal, 2006, Lal, 2010, Seremesic et al., 2011, Lal, 2014). SOC increases the input use efficiency (Govers et al., 2013) and enhances soil resilience to these unfavourable conditions, by improving soil structure, increasing moisture retention and transmission, reducing soil compaction and modulating soil temperature (Six et al., 2002, Manlay et al., 2007, Feller et al., 2012). Furthermore, SOC improves the diversity of soil biota creating disease-suppressive soils (Johnson et al., 2010). To achieve these advantages, it is recommended to retain SOC level in the root-soil-zone above a 2% limit (Loveland and Webb, 2003, Schjønning et al., 2010, Musinguzi et al., 2013). This proportion seems a challenge as it requires a long time frame over which to observe changes, and requires a large amount of organic matter to be retained in soil (SOC constitutes around 58% of the SOM). Duiker (2018) found that increasing the soil

organic matter by 1% a year is unrealistic, but it is achievable to increase it by 0.1%. However, by adding manure or compost, this number will rise significantly. The findings of our research confirmed this positive effect of conservation agriculture on mitigating climate change is explained below.

B) The potential for climate change mitigation: CO₂-equivalent from reduced tillage and residue retention

Considering the total Net Ecosystem Exchange (NEE-GHGs) (by converting into global warming potential in CO₂ equivalent), it was observed in our study that there is a high potential for climate change mitigation from RT. NT and MT had 56% and 40% lower NEE emissions respectively compared to ploughing. This is the first study to explore the effects of the different tillage systems on NEE and the potential for climate change mitigation.

In our study, there was no clear potential from soil emissions alone to mitigate climate change. [Ussiri et al. \(2009\)](#) reported that NT has 51-58% less global warming potential than ploughing after 43 years. In incubational conditions, [Mangalassery et al. \(2015\)](#) found that NT has the potential of reducing 26-31% of GHG soil emissions compared to ploughed soil due to increased microbial activities. Though our results do not support these studies, this is likely due to the fact that the changes in tillage had only been in place for one or two years. Overall, this may mean that the potential for NT alone to mitigate climate change by sequestering carbon may be less than previously thought. Moreover, some of the observed increase is a redistribution of organic carbon, not a net accumulation, with extra organic carbon occurring near the surface, but not always in deeper soil. Consequently, the climate change mitigation achievable from converting to

NT agriculture is likely to be overstated if soil only is considered (as reported by [Powlson et al. \(2014\)](#)).

5.2 The uptake of reduce tillage practices in England and suggestions for policy makers

Despite the evidence on the environmental and financial benefits of RT, RT practices are still not well established on many farms in the UK. The results of the present study estimates that 54.7% of the land in England is cultivated under RT (47.6% under MT and 7.0% under NT). Our results demonstrate that many respondents do not undertake only one form of tillage technique, confirming findings from previous studies such as [Townsend et al. \(2016\)](#). Our study agrees with the results of the 2010 *Survey on Agricultural Production Methods (SAPM)* in Europe ([EuroStat, 2013](#)) and those of [Townsend et al. \(2016\)](#) in England which concluded that RT is more frequently adopted on larger farms due to the financial ability to hold a range of tillage machines at the same time. To some extent, RT adoption is still in the experimentation phase for many farmers. Managers of large farms are more likely to have the ability to take the risk of undertaking new practices on their farms ([Lahmar, 2010](#)) considering the importance of timeliness and cost saving ([Melander et al., 2013](#)).

RT is adopted predominantly on combinable crop farms in comparison to general cropping and mixed crop farms. This is argued to flow from the diversity of the crops grown on one farm as different crops have different tillage and drilling requirements ([Bossange et al., 2016](#)). This creates a burden on farmers to spend more money purchasing a range of required soil preparation machines and also more time to learn the best practice for every crop.

It has been previously observed that there is greater potential of RT uptake in the East of England region (Cannell and Hawes, 1994). Our results confirm that RT is relatively popular with farmers in that region, but it is not an independent influencing factor. The region within which the farm is located was not, in itself, identified as a significant driver of RT uptake although farms in the East of England tend to be larger than other regions.

In this study, it was found that weeds and unsuitable soil types are the main barriers to RT uptake. Farmers respond to these two main problems by using strategic and rotational tillage strategies that include ploughing which may, in part, be responsible for the different estimation of RT uptake observed between different studies. If farmers continue to plough at some stage in the rotation, this will limit the sequestration of the organic carbon on the longer term.

5.3 Recommendation for policy makers to increase farmer uptake

1. To enable the transition from PL to RT practices on farms with smaller land areas; gaining access to RT machinery at reasonable cost will be an important consideration. As the cost of machines required for RT was mentioned as a constraint, long term loans and/or financial governmental support are suggested in order to enable smaller farmers to purchase those machines.
2. As RT uptake is lower on farms where cereals are not the main crops, such as vegetable and root crop (e.g. potatoes and beet) farms, it is recommended that more research be conducted to explore the effects of RT on growth and yield of these crops.
3. RT adoption is a dynamic and multi-faceted process that requires information and demonstration. Farmers need to be better informed about RT. More agricultural

extension is required through having benchmark fields and knowledge exchange platforms in addition to the Agriculture and Horticulture Development Board (AHDB) monitor farm programme. With the rapid increase in social media channels, these could be effective ways to contact farmers, understand their thought processes and influence their decisions. This will enhance the communication between researchers and farmers.

4. The survey suggests English farmers are uncertain about the adoption of RT practices. Over time, farmers can overcome this uncertainty when they get further access to the relevant information and experience. Before that, widespread RT cannot be achieved. [Coughenour and Chamala \(2007\)](#) stated that each farmer needs to make their own changes that suit the conditions on their farms. Thus, further farm innovation will facilitate the spread of RT. This could be through encouraging farmers to have a farm-specific location for trials as it will allow them to observe the result on their own land before full adoption of the new processes ([Uri, 2000](#)).

5.4 Reduced tillage post Brexit

Currently farm subsidies under CAP are largely based on farm area with a small proportion linked to environmental goods (e.g. High Level Stewardship) ([DEFRA, 2015](#)). The UK government is planning to stop this mechanism of subsidies after 2022 and move to payments that are more directly linked to environmental goods ([DEFRA, 2018](#)). The government plans envisage farmers' contribution to higher investment in conserving soil and water resources while maintaining crop production. Encouraging farmers to move to CA could be one of the policy aims as we have shown that CA can reduce GHG and fuel use. It is strongly believed that by undertaking CA, farmers will improve their income

in two ways, 1) through the cost saving of lower usage of machinery and fuel, in addition to the other benefits of RT, and 2) from being eligible for the government support as they would be paid for the “public goods” in relation to climate change mitigation efforts. Lessons can be learned from other regions in the world such as Canada and Brazil where farmers are paid for the ecosystem services including CA ([Kassam et al., 2013](#)) (reviewed in ([Basch et al., 2015](#))).

5.5 The major conclusions from this research are:

5.5.1 The effects of reduced tillage and crop residue retention on GHGs emissions

- There is a high potential for climate change mitigation in the short term of undertaking RT (NT and MT).
- In bare soil, NT increased CH₄ uptake and did not increase N₂O emissions.
- In soil-plant system, NT has positive effects as it reduced CO₂ emissions and increased CH₄ uptake. Moreover, NT did not increase N₂O compared to PL. This means that N₂O was less likely to offset the significant decrease in CO₂ and CH₄ emissions.
- Changes in CH₄ and CO₂ emissions were found to be highly linked to the geometry of the soil architecture, while changes in N₂O were not.

5.5.2 The effects of RT on crop yield

- During the first year of this experiment, the wheat yield was not affected by reduced tillage, possibly due to favourable weather conditions in that season.
- In the second year, a reduction in the triticales yield was observed. This reduction was correlated with some of the soil compaction indicators. The heavy rain in summer (June 2016) during the grain filling stage of crop might have exacerbated

the effects of the compaction. [Crook and Ennos \(1994\)](#) reported that wet soil is unstable and does not afford an adequate foot hold for young roots, therefore lodging happens during the grain filling due to heavy ears and wet soil. However, in the present experiment, lodging was not noticed.

5.5.3 RT uptake by farmers in England

- The study reports that 54.7% of the land in England is cultivated under RT (47.6% under MT and 7.0% under NT).
- Farm size and type are the main factors affecting the uptake of RT on farms in England. Small farms are the least likely adopters of RT, and it is most adopted on large, combinable crop farms.
- Farmer personal characteristics or climate change mitigation potential were not found drivers of RT adoption.
- Soil type is the main driver for which tillage system to undertake on a farm. Weed management and slugs were identified as main challenges for RT adopters.

5.6 Concluding comments

Moving from ploughing to RT helps to reduce GHG emissions and increase organic matter content in the upper 5 cm layer of the soil. This is expected to be extended to the lower soil layers restoring the degraded soil into a sustainable agro-ecosystem environment. The effectiveness of RT and residue retention on soil organic matter and GHG emissions can be seen on the short-term due to an increase in microbial activities and changes in soil structure ([Kandeler et al., 1999](#), [Tran Quoc et al., 2010](#)).

Despite the potential of climate change mitigation of RT, our questionnaire showed that not many farmers are motivated by these benefits. Farmers are more concerned about crop productivity and farm revenues (similar results reported by [Hengxin et al. \(2008\)](#)). Many farmers keep ploughing as it is rooted in their cultural background and also to their lack of knowledge on CA. They often depend on ploughing to bury weed seeds, incorporate chemicals/nutrients mechanically and reduce soil compaction ([Corsi et al., 2012](#)).

If policy makers wish to encourage growers to adopt CA practices, they should incentivise farmers financially. This will need to be achieved by making CA practices paid off as part of the Payment for Environmental Services scheme. This will encourage them to buy reduced tillage equipment and may help them to cover any potential loss in yield, if occurred, before the CA system stabilisation.

6 Chapter: Future work

As a continuation of this work, the results of this work suggest that the following points be undertaken by other researchers.

6.1 GHG emissions

6.1.1 Soil pore characteristics

For the characterisation of the soil pore network, we used the medium size CT scan. The resolution used in this study was 62 μm . This means that pores smaller than this size were not accounted for. Therefore, it is suggested that higher resolution should be used to detect the finer pores which may have a crucial role on the soil biological and physio-chemical properties which govern the soil GHG emissions.

In this experiment, we looked at soil columns 4.5 cm diameter down to a depth of 10 cm. For better representation of the soil structure, we suggest using a higher diameter column. Likewise, deeper soil samples should be included in the effects of the soil structure and not only the upper 10 cm of the soil surface. This will reduce the effects of the destruction during the collection of the soil samples. This is feasible as the same scanner used in this experiment, can scan larger soil samples. However, this requires longer time for scanning every sample. Also, soil aggregate size was not assessed in this work. This is recommended to be included in future research. Furthermore, it is recommended that roots to be analysed simultaneously with measuring the soil physical properties.

6.1.2 The chemical properties of the soil

While this study has included aspects of crop and soil physical properties, it is highly recommended to add the soil chemical and biological properties (including the microbial biomass production) to any future studies. The effects of the soil chemical properties are interlinked with the physical properties and they have inseparable and indispensable influences on soil GHG emissions and crop yield.

6.1.3 GHG plant fluxes

For future work, it is recommended to measure the GHG fluxes of the growing plants using automatic machines such as *Li-Cor*. Measuring plant emissions is important and should be counted in the future work. This will help to investigate the plant physiological impacts on net emissions.

6.1.4 Glasshouse studies

This study was carried out entirely in a field under natural climatic conditions as the climate change mitigation and yield production cannot be separated from weather conditions. Yet, it is suggested that similar measurements be carried out in a glasshouse or a shaded area to avoid any implications of the unusual weather conditions such as heavy rain. This will help also to show the effects of the interaction between soil and plant on GHG emissions and climate change mitigation. In glasshouse, it is more feasible to detect the roots influences on soil organic carbon.

6.2 Crop yield

More research is needed to assess the soil-based environment, in particular short-term impacts, as influenced by RT practices. This includes the organic matter accumulation in the different soil depths. It is also recommended to run the same practices in different geographical areas of England to explore whether RT can protect soil and crops from harsh weather conditions.

Running long-term studies to model the crop production as influenced by different tillage regimes is needed. Modelling helps in predicting how various biological systems will function over time. This would determine which crops will do well in specific geographic locations and whether they will produce enough biomass and grain yield to make their cultivation profitable. For future work, it is suggested using more complicated modelling software which could demonstrate the effects of weather factors.

6.3 Farmer uptake questionnaire

6.3.1 Farmer responses

The postal questionnaire method undertaken in this study seems an effective way to reach a large number of farmers. For future work, interlinking this method with interviews for respondents willing to talk more about their experiences is recommended to collect in depth information about farmers' individual experiences.

6.3.2 RT constraints

Future work should seek to analyse the different factors constraining RT uptake. As holders of small farms are not adopting CA, more work should be done to contact them

and explore the best facilities they may need to start this process. Additionally, as only very few farmers have been found that are committed to CA principles, it is suggested that further case studies be carried out on these farms.

7 Appendices

7.1 Appendix I: the questionnaire's cover letter

Dear (the title and name of the farmer or farm manager),

I am undertaking research into different tillage practices as part of my PhD at the University of Nottingham.

I have enclosed a short survey that I hope you will be willing to complete. The survey asks about your farming practices focusing upon the use of different cultivation practices and reasons for undertaking different cultivations. I appreciate that there are many other demands on your time, so the survey has been designed to take less than twenty minutes to complete and the research will help inform other farmers about the pros and cons of different cultivation practices.

Your answers will be summarised for research purposes and any information provided will remain confidential. Your details will not be shared with any other party*.

The results of this research will be freely accessible after the completion of my PhD studies. If you would like to receive a summary of the findings, plus any published paper from this work, please provide me with your email address. I enclose a pre-paid envelope for you to please return the survey in.

If you have any questions please email me kamal.alskaf@nottingham.ac.uk or call me on 0115 951 6081.

Your contribution to this study is highly valued and appreciated and I hope that the results of the research will be of wide interest to the farming community.

Best regards,



Kamal Alskaf

Contact details

Researcher: Kamal Alskaf, tel. 01159516018 and email: kamal.alskaf@nottingham.ac.uk

Principal Investigator or supervisor: Prof. Paul Wilson, tel. 01159516075 and email: paul.wilson@nottingham.ac.uk

Principal Investigator or supervisor: Dr. Debbie Sparkes, tel. 01159516074 and email: Debbie.sparkes@nottingham.ac.uk

Complaint procedure

If you wish to discuss the way in which the research is being conducted or have any concerns about the research then in the first instance please contact Prof. Paul Wilson, tel. 01159516075 or email: paul.wilson@nottingham.ac.uk. If this does not resolve the matter to your satisfaction then please contact the School's Research Ethics Officer, Dr Kate Millar, tel. 0115 951 6303, email Kate.Millar@nottingham.ac.uk

* You have been randomly selected from a list of farmers obtained from the Experian data base.
[www.experian.co.uk]

7.2 Appendix II: the questionnaire

Tillage practices in the UK.

This survey aims to understand UK farmers' attitudes to different tillage practices and to identify any barriers to the uptake of zero tillage.

Part 1 – Farm data

- 1 What is the total area of farmland that you are managing?

	Hectares
	Acres

or

- 2 In which county/ies of England is your farm located?

--

- 3 What is your farm type? (Please tick one only)

Combinable crops	
General cropping (e.g. a mix of cereal crops, root crops, etc.)	
Predominantly livestock	
Mixed farm (crops and livestock)	
Other, please state	

- 4 Farm tenure (Please tick one)

Own all land	
Tenant all land	
Mixed tenure	

Part 2– Farmer characteristics

5 What is your age? (Please tick one)

<25 years	
25-34 years	
35-44 years	
45-54 years	
55-64 years	
65-74 years	
>75 years	

6 How many years have you been managing your farm or farm enterprise?

Less than 10 years	
10-20 years	
20- 30 years	
30- 40 years	
More than 40 years	

7 What is your gender?

Male	
Female	

8 What is your highest educational qualification?

GCSE/ A level	
Diploma	
BSc degree	
MSc	
PhD	
Others, please specify....	

Part 3– Tillage and Crop Establishment

9 What proportion of your arable area is cultivated using the following techniques?

	0%	1-20 %	20-40 %	40-60 %	60-80 %	80-100 %
Zero tillage/direct drilling						
Reduced/minimum tillage						
Plough-based						

In this study we are using these definitions:

Zero tillage/direct drilling: sowing directly into the residues of the previous crop without any prior topsoil loosening.

Reduced/minimum tillage: loosening the soil surface without inverting the top soil.

Plough-based: inverting the soil surface before sowing.

10 In general, what tillage practices do you use for each of your crops?

Crop type	Tillage practices	No. of passes	Average tillage depth if known
<i>E.g. first winter wheat</i>	<i>Plough</i>	<i>1</i>	<i>30 cm</i>
	<i>Power harrow</i>	<i>2</i>	
	<i>Roll</i>	<i>1</i>	

If you cultivate with zero or reduced/minimum tillage on any of your land, please move on to **question 11.**

If you cultivate with a plough based system **only**, please move on to **question 20, page number 7.**

11 How many years have you been undertaking zero/minimum tillage? Please tick one

	zero tillage	minimum tillage
Less than 5 years		
5-10 years		
10- 15 years		
More than 15 years		

12 How did you learn about the techniques of zero/minimum tillage? Please tick all that apply.

	Yes	If yes, please specify
Other farmers		
Self-experimenting		
Internet		
Social media		
Companies		
Organisations		
TV programmes		
Farming press		
Cereals event		
Others,		

13 What changes have you observed from using zero/minimum tillage? (Please tick as many as you want).

	Increased	Decreased	No change	Not monitored
Yield				
Fuel consumption				
Timeliness				
Crop establishment				
Straw amount produced				
Soil organic matter				
Weeds e.g. black grass problems				
Workload compared to ploughing				
Earthworm population				
Soil temperature				
Soil moisture				
Fertilisers needed				
Nutrient availability to next crop; especially soil mineral nitrogen.				
Profits				
Others, please specify				

- 14** What do you perceive to be the most important outcome from using zero/minimum tillage?

--

- 15** If you plough your land from time to time, when do you normally plough?

	Before			After		
	Always	Sometimes	Never	Always	Sometimes	Never
First winter wheat						
Second winter wheat						
Spring wheat						
Winter oilseed rape						
Winter barley						
Spring barley						
Maize						
Other cereals						
Field beans/peas						
Root crops						
Grass						
Others, please specify.						

- 16** When deciding whether or not to plough, which factors are important? (Please tick as many as apply)

	Not important at all	Not important	Neutral	Important	Very important	
Weather						N/A
Weeds						N/A
Climate change						N/A
Water availability						N/A
Machine availability						N/A
Crop varieties						N/A
Labour availability						N/A
Soil nutrients						N/A
Prominent soil type						N/A
Soil organic matter						N/A
Other, what are they?						
						N/A

Part 4: Straw use/incorporation

17 What do you normally do with your straw?

Crops	Chopped and added to the field	Baled for own use	Sold (off farm)	Swapped for muck
<i>e.g. triticale</i>	50%	20%	10%	20%
Wheat				
Barley				
Oilseed rape				
Triticale				
Peas				

18 Does straw use factor into your decisions regarding tillage practices (whether the straw is baled or not)?

Yes	
No	

If no then please skip **question 19** and move onto **question 20** if applicable.

If yes, how does straw use influence your decisions regarding tillage practices and vice versa?

19 If you incorporate cereal straw have you noticed any benefits /disadvantages of straw incorporation?

	Increased	Decreased	No change	Not monitored
Earthworm numbers				
N requirements				
P and/or K requirements				
Water drainage				
Nitrogen leaching				
Slug damage to crops				
Ease of cultivations				
Effectiveness of straw burial				
Soil structure				
Others, what are they?				

If you have any plough based tillage, please carry on to **question 20**. If not, thank you very much for your time. Please put the survey in the envelope provided and kindly send it back.

Part 5 – Barriers to the adoption of zero/minimum tillage

20 Have you ever tried zero/minimum tillage practices?

	Using	Tried	Not using or tried
Zero tillage			
Reduced/minimum tillage			

If you have used or tried zero/minimum tillage , please carry on to question 21. If you have not, please move on to question 24

21 What are the challenges you faced/facing from zero tillage (not minimum tillage)? (Tick as many as apply, or move to question 24 if you do not/have not used zero tillage).

	✓
Lower yields	
Poor crop establishment	
Increased weeds burden	
Increased disease problems	
Increased incidence of rabbits	
Top soil compaction	
Increased incidence of slugs	
The field was perceived untidy	
Others, what are they?	

22 What are the challenges you faced/facing from minimum tillage (not zero tillage)? (Tick as many as apply, or move to question 24 if you do not/have not used minimum tillage).

	✓
Lower yields	
Crop establishment was poor	
Increased weeds burden	
More crop diseases	
Increased incidence of rabbits	
Increased incidence of slugs	
The field was perceived untidy	

- 23 What are the factors that have prevented you from adopting zero/minimum tillage? Please tick all that apply.**

Lack of information.	
Not convinced that zero/minimum tillage is better for the environment.	
I am satisfied with my current production (methods and yields).	
Investment in machines required.	
Ploughing is needed to control black grass and other weeds.	
Lack of government support for these techniques.	
Concern of reduced yield.	
Concerns about increasing slugs	
My crops will be perceived untidy.	
Advised against it from other farmers and or advisers	
Others, what are they?	

- 24 What would most persuade you to stop ploughing and start or increase the use of zero/minimum tillage? Please tick one.**

Governmental incentives e.g. government grants for machinery	
More information	
Training on practices	
Availability of affordable machinery	
Availability of specialist contractor	
Others please specify:	

- 25 If you want to start or increase the use of zero tillage, what would be your motivations? Please tick the most 3 important.**

	Very important	Important	Not important
Maintain environment and climate change mitigation.			
Resource conservation such as water and soil.			
To increase soil organic matter			
It is better for the health of soil in general			
Increasing crop yield			
Reduced fuel consumption			
Reduced workload/timing			
Reduce soil erosion			
Others, please specify			

The following box is provided if you would like to provide any further comments on your tillage practices.

Thank you very much for your time. Please put the survey in the pre-paid envelope provided and kindly send it back.

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