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# Optimising conservation tillage systems for wheat and oilseed rape production

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# Abstract

The aims of the thesis are to determine the effect of different conservation tillage systems on the agronomic, environmental and economic performance of a wheat and oilseed rape rotation, and to understand the processes involved so that the systems can be improved. The field research examined five systems over three seasons (September 2013 to August 2016) in two fields (one clay and one clay loam) in Northamptonshire. The most disruptive tillage treatment was the Farm system comprising the use of a Sumo Trio when establishing oilseed rape, and the Sumo Trio and a Kuhn seed drill when establishing wheat. The least disruptive system was a Väderstad Seed Hawk or Rapid. The other three treatments were all one pass conservation tillage systems comprising a Claydon Hybrid Drill, a Mzuri Pro til 3, and a Sumo Deep Tillage Seeder (DTS). To understand the effect on draught and soil disturbance, specific components of the systems were tested under controlled conditions at Cranfield University's soil bin facility. The shallow working Väderstad required the lowest draught and disturbed less soil than deep working treatments. A low aspect ratio (working depth/implement width) and rake angle reduced the draught. In the field immediately after tillage, the Farm system showed the greatest reduction in bulk density and penetration resistance at 0-50 mm and 150-200 mm, but this effect was not maintained during the season. The level of surface residue was lowest (15%) with the Farm system and greatest (75%) with the Väderstad. The shallow Väderstad led to the highest earthworm abundance in all years and both fields, proportions of water stable aggregates and microbial biomass carbon in third and first year respectively. In the clay field, blackgrass infestation doubled from 8.2% in 2013-14 to 16.0% in 2015-16; it was not a major problem in the clay loam field. Due to high variability, there was no significant effect ($p>0.05$) of tillage treatments on the yield of wheat and oilseed rape over the 3-year trial period in either field, except when delayed drilling of oilseed rape with the Sumo DTS in September 2015 which led to reduced yields. At a reduced significance level of $p=0.15$, higher yields observed for Väderstad and Mzuri in the clay soil were associated with higher levels of organic matter. The relative profitability of the five systems was primarily determined by the assumed yields and secondly by the cost of the systems. The predicted annual net margin for the five systems varied from £545 to £659 ha$^{-1}$. The calculated cost of the five tillage systems (assuming working areas ranging from 370 to 1,100 ha) ranged from £11 to £31 ha$^{-1}$ a$^{-1}$, with the lowest cost achieved by the 6 m Claydon system. Assuming blackgrass weeds are not an issue, shallow low disturbance systems can result in low costs, improved soil biology and carbon storage, and sustainable high yields.

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# List of Abbreviations

| | |
|---|---|
| WW | Winter wheat |
| OSR | Oilseed Rape |
| FS | Farm system |
| MBC | Microbial Biomass Carbon |
| TOC | Total Organic Carbon |
| WSAGG | Water Stable Aggregates |
| BD | Bulk Density |
| PR | Penetration Resistance |
| NPV | Net Present Value |
| NDVI | Normalised Difference Vegetation Index |
| R | Revenue |
| Y | Crop Yield |
| G | Grain marketable price |
| V | Variable costs |
| A | Assignable fixed costs |
| ROI | Return On Investment |
| HI | Harvest index |

# 1 INTRODUCTION

*"It is not ploughing, it is not digging, it is not harrowing, raking, hoeing, rolling, scarifying, clod-crushing, scuffling, grubbing, ridging, casting, gathering that we want: all these are the time honoured, time bothered means to a certain result. The result is - a seed bed"* (Hoskyns, 1865, quoted by Culpin, 1936).

## 1.1 Background

Wheat and oilseed rape are the principal arable crops in the UK. The area of winter wheat in 2014 was 2.0 million hectares, whilst the area of oilseed rape was 700,000 hectares (HGCA 2014) (Figure 1.1). Together these represent 15.8 % of the agricultural arable area in the UK. In 2014 within the EU, wheat covered 27 million hectares and oilseed rape 6.8 million hectares (USDA, 2017). In the same year and globally, the area of wheat was 220 million hectares and that of oilseed rape 35 million hectares (National Agricultural Statistics Service 2015; USDA 2017)

Figure 1.1. Oilseed rape and wheat cultivation in the UK

Over many years, in various countries around the world, a large amount of research effort has been directed towards increasing arable crop yields per unit area, minimizing the negative impact on the environment, and maximizing the economic benefit (Burgess and Morris 2009; Curtis et al. 2014; Gou et al. 2017; Morris and Burgess 2012; Mann & Warner 2017).

For a given agro-climatic environment, increasing crop yields per hectare can be obtained from improved crop varieties, changes in the timing and spatial configuration to maximize resource capture (e.g. earlier drilling dates, new plant varieties), the reduction of abiotic and biotic stress (e.g. improved nutrition, reduced weed and pest competition, the use of rotations), and more effective harvesting methods (Du & Tebru 1999; Rieger et al. 2008; Calado et al. 2010; Prihar et al. 2002; Burgess and Morris 2009). During the last decades of the twentieth century and the start of the twenty-first century there has also be increased awareness of the need to minimize negative environmental costs (Burgess and Morris, 2009). This includes the minimization of greenhouse gas emissions, and the minimization of nitrate, phosphorus, and pesticide losses. However agricultural systems that provide high yields and enhance the environment will only be widely adopted by farmers if they are cost-effective for individual businesses.

In the production of wheat and oilseed rape, a key management decision is the type, intensity and frequency of the tillage system. Because it affects the soil environment surrounding the germinating seed and growing seedling and the timeliness of operations, it can affect the yield per hectare. The tillage system has environmental implications and it also determines the labour and energy inputs.

Kõller (2003) argues that reduced tillage systems are being considered by farmers because of concerns about the soil's physical, biological and chemical quality, including the soil organic matter content. Tillage techniques can affect soil physical properties such as soil structure, strength and bulk density. In turn, these have been shown to affect rates of crop germination, establishment and growth (Fuentes et al. 2009; Aikins and Afuakwa, 2012).

In general terms, the type of tillage can range from ploughing (where the soil is inverted) to conservation tillage systems where soil is not inverted and disturbance is minimized. The literature review, in Chapter 2, reviews the different types of tillage systems. As Knight eKnightt al. (2012) studied in the UK, reduced tillage practices were popular in the 1980s (Figure 1.2), but their use declined and the use of ploughing increased in part due to the need to control weeds such as blackgrass (*Alopecurus myosuroides*). However since 1996, the area of winter wheat planted using reduced tillage has increased, reaching about 40% of the area in 2008 (Knight et al 2012). This is primarily driven by the need to reduce the costs of crop establishment and the opportunity to improve the timeliness of operations (Baker et al. 2007). In contrast to the increased area of reduced tillage, the area of “no-till” directly drilled wheat has remained low.

As Mal & Hesse (2015) reported, reducing labour use can improve the social life of farmers. In the peak times of harvesting and drilling, labour requirements are greater in a conventional rather than a conservation tillage system. Farmers can reduce labour pressure through conservation tillage practices. They can use this labour or time savings for other choices like social events or other business activities. Conservation tillage also can be more helpful where there is labour scarcity. One disadvantage of conservation tillage can be the need for higher pesticide use (Küstermann, Munch and Hülsbergen, 2013).

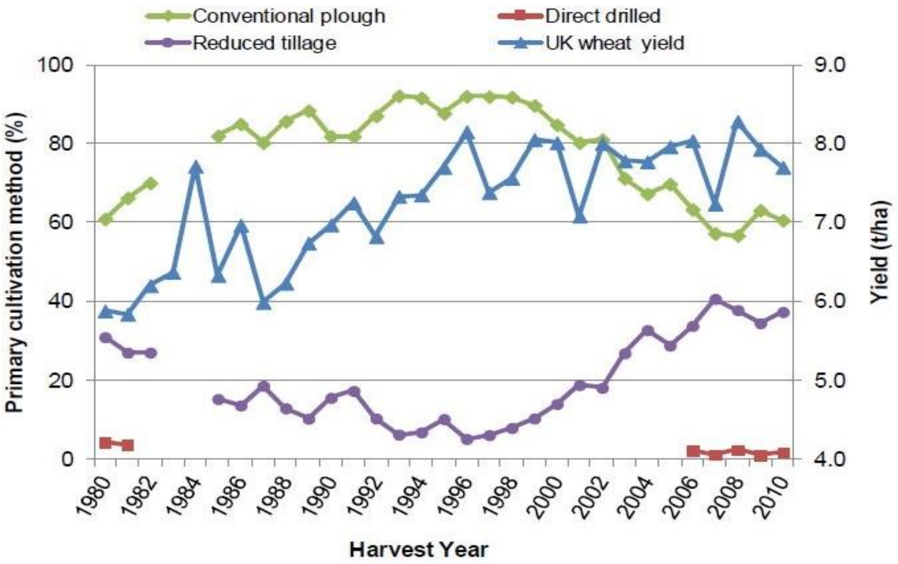


Figure 1.2. Proportion of winter wheat area established using various establishment methods in UK (after Knight et al. 2012)

## 1.2 Aim, objectives, and research gaps

Frontier Agriculture is a large crop input and grain marketing business owned jointly by Associated British Foods and Cargill plc. They provide agronomic advice throughout the UK through a team of about 110 agronomists, and hence they have a strategic and applied interest in understanding the impact of tillage systems.

The price of diesel (before VAT and duty) in the UK increased from 19 pence per litre in December 2003 to 60 pence per litre in November 2012 (DECC, 2014). Fuel price has implications on what will be the most profitable tillage systems at any one time (Knight et al. 2012).

Frontier Agriculture was keen to know: how do commercially-available conservation tillage systems in the UK affect the agronomic, environmental and economic performance of winter wheat and oilseed rape production? In order to address these questions, Frontier agreed to sponsor a three-year PhD program with the support of Lamport Hall and Moulton College in Northamptonshire.

From an initial review of the literature, it was apparent that many soil characteristics such as bulk density, penetration resistance and organic carbon have both agronomic and environmental implications. Hence there was an initial appreciation that tillage will have soil and crop effects and agronomic, environmental, and financial implications (Figure 1.3).

The research gap that the study aims to fill, has four pillars: i) it was carried out an integrated assessment of agronomic, soil and economic parameters. The economic assessment involved a cost-benefit analysis of the tillage treatments and monitored the energy use of the main tillage implement of each treatment. ii) The study was carried out under commercial conditions, iii) involved two soil types and examined the effects of the monitored parameters on iv) a wheat - oilseed rape rotation.

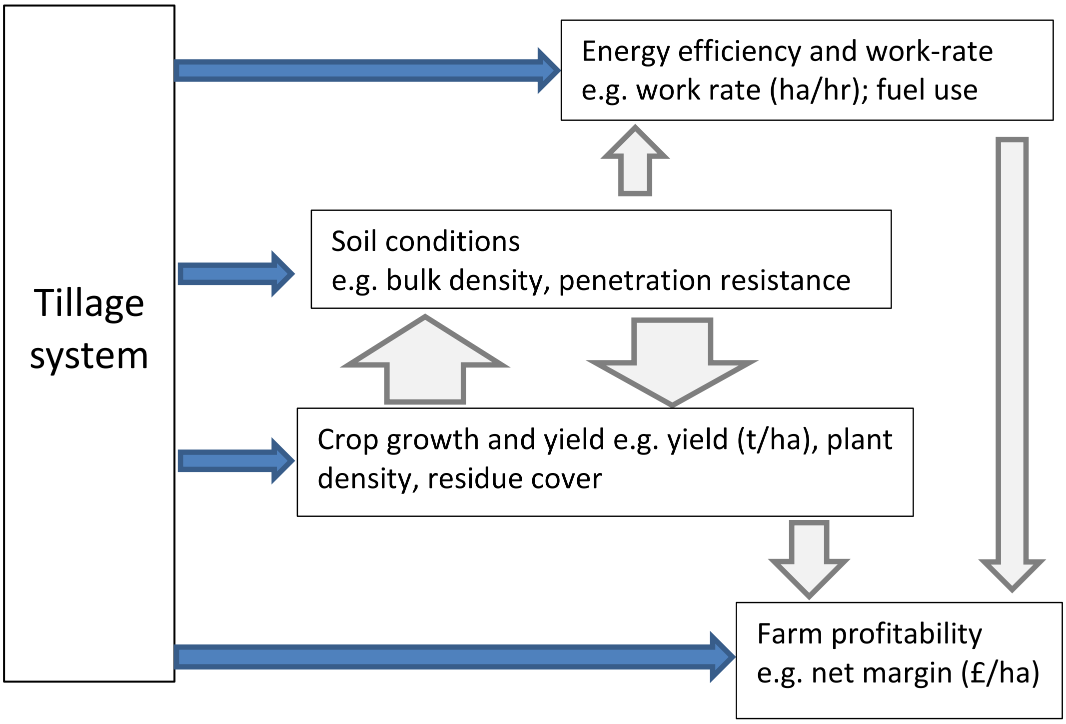


Figure 1.3. The tillage system affects soil conditions, crop growth and yield, energy efficiency, and farm profitability

### 1.2.1 Aims

The research question posed by the sponsor forms the first, more applied, aim of this thesis:

1) to determine the effect of different conservation tillage systems on the agronomic, environmental and economic performance of a wheat and oilseed rape rotation.

However this research was undertaken as a PhD and hence in order for the research to have wider significance, there was also a focus on improving the understanding of **how** tillage affects soil characteristics, crop performance, and farm profitability. Hence the second, more strategic, aim was:

2) to understand the processes involved to improve the agronomic, environmental and economic effects of conservation tillage systems

### 1.2.2 Objectives

In order to address the aims, a series of objectives and research hypotheses were proposed. The applied aim was to be addressed by three objectives and their evaluation was carried out against each tillage treatment. These were to determine the effect of commercially available conservation tillage systems:

1) on soil condition in a wheat-oilseed rape rotation
2) on crop growth and yield in a wheat-oilseed rape rotation
3) on energy efficiency and profitability in a wheat-oilseed rotation.

To address the strategic aim, the final two objectives were:

4) to understand how different conservation tillage systems affect soil conditions, crop growth and yield, and profitability, and
5) to identify how the configuration and use of conservation tillage can be optimised.

### 1.2.3 Research hypotheses

The first three objectives were to be addressed through three research hypotheses:

1) Conservation tillage systems have different effects on soil condition
2) Conservation tillage systems have different effects on crop growth and yield, and
3) Conservation tillage systems have different effects on farm profitability

The first two research hypotheses were examined by field experimentation, and the third hypothesis was examined by the use of field data in a financial model.

### 1.2.4 Expected outputs

This anticipated outputs were the provision of guidance:

- to farmers and advisors, of the costs and benefits associated with the tested tillage systems,
- to manufacturers, of the strengthens and weakness of tillage systems, and
- to government about how conservation tillage can contribute to sustainable intensification.

## 1.3 Structure of the thesis

The thesis comprises eight chapters; the first three chapters describe the background the aim, objectives, the literature review and the methodology. Whilst replicated field studies are instructive to understand the profitability and environmental impacts of conservation tillage, the inherent variations in soil conditions across a field can confound the soil and plant responses to different types of tillage equipment. The soil and water management facility (soil bin) at Cranfield University (Chapter 4) offered the potential to study the effect of different types of tillage equipment (including various designs of seed drills and machinery configurations), in terms of force requirements, forms of soil loosening and degree of soil disturbance. Chapters 5 and 6 describe the field results in terms of soil condition and crop growth. Chapter 7 describes energy efficiency in the field and uses the results from previous chapters to compare the profitability of the different systems. Finally Chapter 8 describes how the objectives were met and presents recommendations for further research (Figure 1.4).

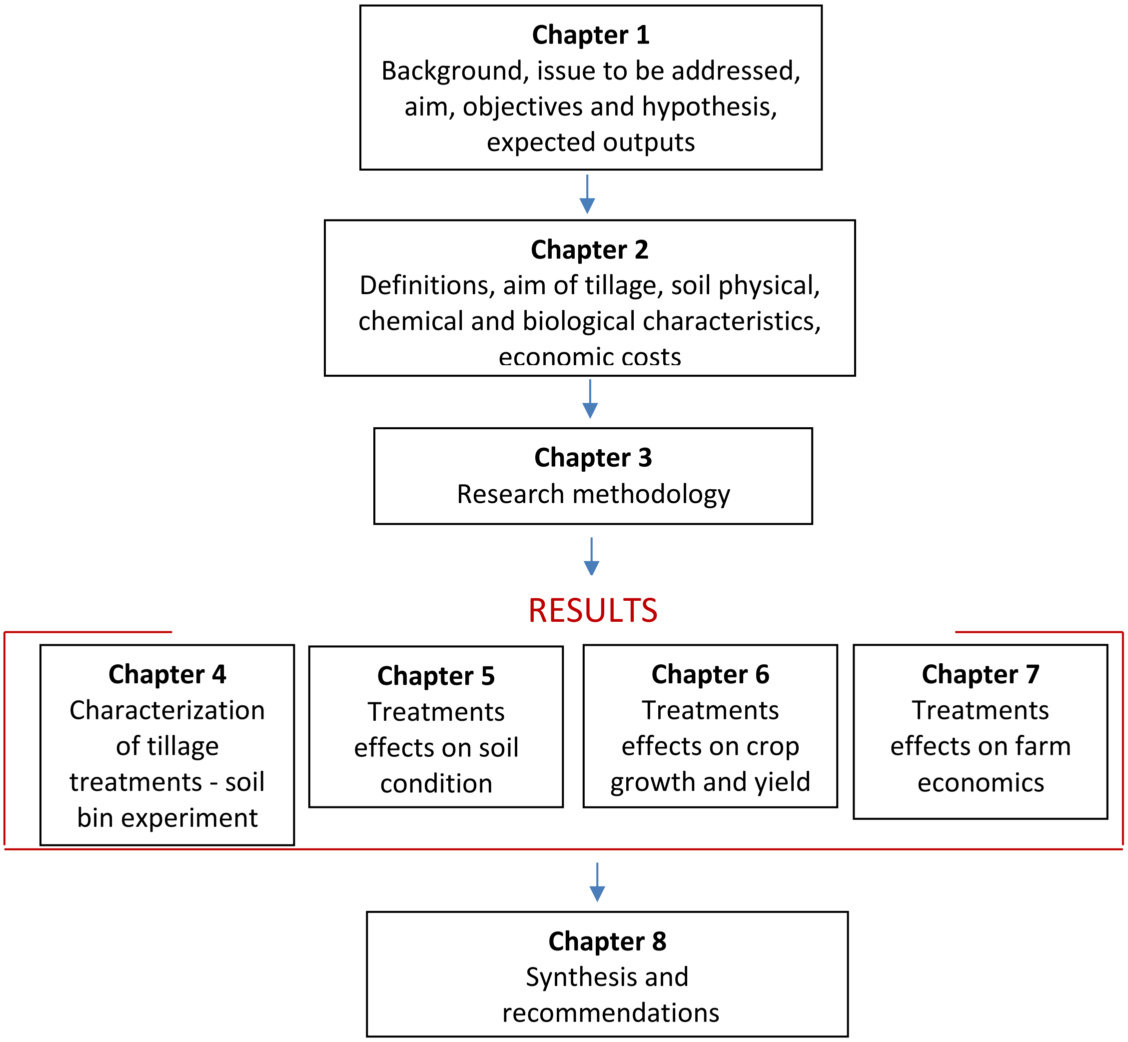


Figure 1.4. Flow chart illustrating organization of the thesis structure

# 2 LITERATURE REVIEW

This section starts with a brief review of crop rotations and frameworks for analysing crop yields per hectare.  It then reviews the definition of “tillage” and the key types of tillage.  The third section highlights the key objectives of using tillage in crop production and the advantages and disadvantages of tillage and different tillage systems are then reviewed in terms of five areas: soil properties, soil surface characteristics, weed, pest and disease control, the biology and chemistry of the crop-soil ecosystem, and economics.  The final section clarifies the research questions, hypotheses and objectives of the PhD study.

## 2.1 Crop rotations and factors determining crop yields

### 2.1.1 Crop rotation

In most parts of the world there is usually one arable crop that is more profitable than other crops. In many parts of Eastern England the most profitable arable crop is winter wheat. However farmers are unable to grow winter wheat continuously because of the build-up of disease and weed populations. Hence farmers typically practice a crop rotation which has been described as “growing crops in a recurring sequence on the same field” (Thenail et al. 2009).

Crop rotations can help with chemical weed control as it can be easier to control cereal and grass weeds in a broad-leaved crop like oilseed rape and beans, and it can be easier to control oilseed rape weeds in a cereal crop. Because of greater variability in the type and timing of soil, crop, and weed management practices, there are more opportunities for weed mortality events in rotations than in monoculture (Martin and Felton, 1993). Onstad et al. (2001) also highlights that crop rotations can help with pest management as individual species are less likely to proliferate in two crop species than individual crop species. In a review of weed dynamics, Nichols et al. (2015) concluded that crop rotations and surface residue retention are both methods of weed control. They showed that no-tillage should not be implemented in monoculture systems due to weed problems. From the same perspective, Cardina et al. (2002) report that crop rotation was a more important determinant of weed - seed density than the type of tillage system. There are various general models or frameworks for explaining the key determinants of crop yield per hectare. Three models are outlined below.

### 2.1.2 Incident solar radiation approach for yield measurement

Monteith and Moss (1977) related the annual yield ($Y$; g m$^{-2}$), to the annual incident solar radiation ($S$; MJ m$^{-2}$), the proportion of the radiation that is intercepted ($f_s$) (which is primarily determined by the Leaf Area Index), the radiation use efficiency ($\varepsilon_S$; g MJ$^{-1}$), and the harvest index ($HI$) (Equation 2.1).

$$Y = S.\,f_S.\,\varepsilon_S.HI \qquad \text{Eq. (2.1)}$$

Equation 2.1 can be used to highlight how seasonal differences in solar radiation and timing of drilling affect yield. Everything else being equal, increasing the duration of the cropping period (i.e. earlier drilling or later harvest) will increase the capacity of the crop to intercept solar radiation. Likewise locations with higher levels of solar radiation can be expected to have higher yield potentials. One of the key parameters determining the proportion of light intercepted ($f_S$) is the leaf area index. The leaf area index is a dimensionless variable defined as the total one-sided area of photosynthetic tissue per unit ground surface area (Jonckheere et al. 2004). However, light interception by the crop is also affected by weed competition. Blackgrass (*Alopecurus myosuroides* Huds) is a common weed in cereal rotations in Europe and is frequently found in fields on heavy e.g. clay soils (Colbach & Sache 2001; Chauvel et al. 2001; Menchari et al. 2006) Previous work has shown that blackgrass competition is a serious issue in winter wheat grown under conservation tillage particularly on clay soils (Davies and Finney, 2002). Blackgrass is considered to be competitive to wheat yields at populations of about 2-20 heads m$^{-2}$ and above (Bayer CropScience, 2012). The ratio of the amount of crop dry-matter produced per unit of intercepted photosynthetically active radiation is usually referred to as radiation-use efficiency, $\varepsilon_S$ (Stockle and Kiniry, 1990). A crop's harvest index ($HI$) is defined as the ratio of economical yield (grain) to total above ground biomass (Morgan et al. 2010). For a wheat crop, the harvested component is the grain; for an oilseed rape crop, the harvested component is the oilseed. However farmers are also interested in the oil content of the oilseed. Most buyers of oilseed rape in the UK pay a financial premium for every 1% of oil content above 40%. A similar deduction is made for loads with oil contents below 40%. Thus, growers can achieve higher returns on their crops by increasing either seed yields or oil contents (HGCA, 2006).

### 2.1.3 Water use and yield

In locations where there is limited water, it can also be useful to relate crop yield to the use of water. The yield ($Y$; g m$^{-2}$), to the available water ($W$; m$^{3}$ m$^{-2}$), the proportion of water transpired by the crop ($f_{w}$), the transpiration efficiency ($\varepsilon_{w}$; g m$^{3}$), and the harvest index ($HI$) (Equation 2.2).

$$Y = S.\, f_{w}.\, \varepsilon_{w}.\, HI \qquad \text{Eq. (2.2)}$$

The temporal distribution of rainfall is important as it can affect both the proportion of water transpired by the crop and the harvest index; the transpiration efficiency can be relatively consistent.

### 2.1.4 Plant component approach to yield measurement

An alternative method of explaining crop yield is in terms of yield components. For example, in the case of wheat, the yield per m$^{2}$ ($Y$; g m$^{-2}$) is dependent on the plant density (plants m$^{-2}$), the number of ears per plant, the number of grains per ear, and the mean grain weight (g per grain) (Equation 2.3).

$$Y = \text{plant density x ears per plant x grains per ear x mean grain weight} \qquad \text{Eq. (2.3)}$$

At very low plant densities, a doubling in plant density may be expected to lead to a doubling in yield. However as the plant density increases, further increases in plant density can result in a lower number of ears per plant or grains per air. In fact, if there is a minimum plant size that is needed to ensure yield, then high densities can eventually cause a decrease in crop yield. In addition, lodging and increased disease incidence can cause yield decreases (Leach et al. 1999). Hence grain yield per unit area can respond to plant density in a curvilinear fashion (Dong et al. 2010; Ciampitti and Vyn, 2011). The seed rate depends on the thousand grain weight and the target plant population. UK optimum seed rate for oilseed rape is considered to be around 50 seeds m$^{-2}$, and the optimum for winter wheat around 300 seeds m$^{\mathbf{-2}}$ (AHDB Cereals & Oilseeds 2015**;** HGCA 2014b; Theobald et al. 2006**;** Bayer 2016)**.** Koch et al. (2009) found that reduced tillage led to a reduction in plant density which decreased yields. Romaneckas et al. (2009) also found that germination of directly sowed seeds was 37% less compared with conventional ploughing. However because of the resulting "more optimal" density, the final yield was higher in the no-tilled tillage treatment.

## 2.2 What is tillage and what are the options?

The word "tillage" is generally used in this thesis in preference to "cultivation" which has the ambiguous meaning (in the Oxford English Dictionary) of both "breaking up the ground" and "raising and producing crops".

Weise and Bourarach (1999) define tillage as "the preparation of the growth zone in the soil (about 10 to 90 cm of the top layer of soil) for plant development". Theoretically this definition would imply that the application of nutrients to the soil (if it prepares the growth zone) is tillage; however most people would not consider that to be tillage. Buckingham (1976) defines tillage as "*those mechanical, soil stirring actions carried on for the purpose of nurturing crops*". Tne (1984) defined tillage as any physical loosening of the soil carried out in a range of cultivation operations, either by hand or machine. However some tillage operation may seek to make the soil firmer. Baker et al. (2007) write that "most people understand tillage to be a process of physically manipulating the soil". Each of these definitions place emphasis on a physical process.

### 2.2.1 Types of tillage system

Seedbed preparation can be carried out in two ways, i) seedbed preparation alone (Figure 2.1a) and ii) seedbed preparation and drilling in one operation (Figure 2.1b) (Loren et al. 2011). Tillage systems should allow smooth seedbed conditions, providing appropriate depth, seed spacing control, seed-soil contact and minimal crop residues within the seed slot. In addition, the soil above the seed must remain sufficiently loose for the seedling to grow up through the soil, and the pore space around the seed must contain sufficient large pores to maintain good aeration and to allow the easy growth of rootlets (National Soil Research Institute, 2001).

Figure 2.1. a) Seedbed preparation alone (left) and b) seedbed preparation and drilling in one pass (right)

The first way of seedbed preparation usually includes two or more passes to plant the seeds. The first pass manipulates the soil in terms of breakage of clods and the incorporation of crop residues whilst the second pass, carried out by different equipment, drills the seeds. The second way of seedbed preparation combines the soil preparation and seeding in one operation often with pneumatic seed drills. In the literature, there are multiple and often confusing names for different tillage systems (Table 2.1). Davies & Finney (2002) reported that current tillage systems can be divided into two broad categories: inversion tillage, known as conventional plough tillage, and non-inversion tillage known as conservation tillage including minimal tillage and direct drilling. The Conservation Technology Information Center (CTIC, 2002), Gajri et al. (2002)

and USDA (2007) underline that any tillage and drilling system that leaves 15% or more of the soil surface covered with crop residue after drilling is referred to as conservation tillage. Kertész et al. (2010) highlights that conservation tillage encompasses a range of tillage practices including “zero (no) tillage”. Shamsudheen (2013) describes conservation tillage as any tillage practice that reduces soil or water loss when compared to ploughing, while Putte et al. (2012) reports that conservation tillage seeks to reduce soil disturbance and to maximize soil cover by residues. Soane et al. (2012) refer to “no-till” or “zero-tillage”. Other authors refer to “reduced tillage” or to the general term “conservation tillage”. Table 2.1 describes the key forms of tillage practices in the UK and organises them in terms of their main characteristics.

Table 2.1. Characteristics of inversion tillage, reduced tillage, and no tillage systems according to selected references

| **Tillage System** | **Residue cover (%)** | **Other characteristics** | **Conservation Tillage?** | **Reference** |
|---|---|---|---|---|
| **Inversion tillage** | <15 | Residue incorporation<br>Prevents growth of all plants except the particular crop being raised | No | (Gajri et al. (2002); Kõller, (2003)) |
| **Reduced tillage*** | 15-30 | One or more tillage trips, disturbs all of the soil surface | No | (CTIC 2002; Lobb et al. (2007)) |
| | 15-30 | Minimum disturbance<br>Modern practice emphasizes the amount of residue retention | Yes | (Kõller, (2003); Baker et al. (2007)) |
| | About 30 | Eliminate operations compared to conventional tillage<br>Residue cover varies around 30% | Yes | (D’Haene et al. (2008)) |
| **Strip tillage** | >30 | A strip is tilled and planted and the ground between rows is left undisturbed | Yes | (Licht and Al-Kaisi (2005); Norberg (2010)) |
| **No tillage** | >30 | < 5% soil disturbance | Yes | (Soane et al. (2012); Kõller, (2003)) |
| | | No primary or secondary tillage other than the “no till” planter | Yes | (Mahboubi & Lal (1998)) |

*For the purpose of this thesis – reduced tillage is classified as conservation tillage system

Building on the analysis of tillage types in Table 2.1, this thesis uses the following nomenclature:

*Inversion or traditional tillage* involves inversion of the soil normally with a mouldboard plough as the primary tillage operation, followed by secondary tillage to create a seedbed.

*Reduced or minimum tillage* systems include one or more passes of tillage equipment without inverting the soil before drilling and the level of residue cover is typically 15-30%. It is possible to distinguish between systems that comprise i) a single pass and ii) those using two passes where the cultivation occurs separately from seed placement.

*Strip-tillage* is a system in which residue-free strips of soil (typically about a third of the row width) are disturbed using an implement or blade, such as a fertilizer injection shank, which are then planted. The residue-free strips differ in width depending on the crop and the implement normally penetrates to a depth of 10 to 20 cm (4 to 8 inches).

*No-tillage, zero-tillage, or direct drilling* involves drilling seeds without any prior loosening of the soil by cultivation other than very shallow disturbance (< 5 cm) by the drill coulters. Here, typically 30-100% of the soil surface is covered with plant residues (Soane et al. 2012).

## 2.3 What is the aim of tillage?

Baker et al. (2007) explain the aims of tillage are "*to achieve weed control, fineness of tilth, smoothness, aeration, artificial porosity, friability and optimum moisture content so as to facilitate the subsequent sowing and covering of the seed*". However other definitions indicate that the aims of tillage extend beyond seedling establishment. Lal (1973) writes that tillage includes all operations of seedbed preparation that optimize soil and environmental conditions for seed germination, seedling establishment and crop growth. Tivy (1990) even extends this to harvesting saying that the aims of tillage are "*to create soil conditions that will facilitate seed germination, seedling emergence and root development, inhibit or destroy competitive organisms such as weeds, pests and pathogens; and allow crops to be cropped or harvested easily and in good condition*". Antapa et al (1990) argues that the overall goal of tillage is to increase crop production while conserving resources (soil and water) and protecting the environment.

### 2.3.1 Categorising the advantages and disadvantages of tillage

Various authors have tried to explain the potential advantages and disadvantages of tillage. For example Spoor (1975) made a distinction between "positive" and "negative" cultivation. The advantages and disadvantages of tillage can be related to i) soil physical characteristics, ii) the soil micro-topography, iii) weed, pest and disease control, vi) the chemistry and biology of the crop-soil ecosystem, and v) economics. These issues and the benefits and disadvantages of conservation tillage are described in Table 2.2.

Soane et al. (2012) underlined that the successful adoption of no tillage depends on successful handling of plant residues, weed control, compaction control, and the correct selection and use of herbicides and direct drill equipment. The soil compaction is the physical form of soil degradation that changes the soil structure and influences the soil productivity (Mueller et al. 2010). Soil compaction 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" (SSSA, 2008). So, the soil compaction involves the changes in physical properties of the soil (bulk density and soil porosity) and these modified physical parameters of the soil are determinants of the influence of the soil compaction on chemical properties of the soil, soil fauna, and diversity and plant growth (Farrakh Nawaz et al. 2012).

In modern agriculture, most of the field operations from sowing to harvesting are done mechanically by using heavy wheeled machines which can compact the soil at every passage (Williamson and Neilsen, 2000). The soil compaction by a machine, in general, depends on the soil strength and loading of machine (Alakukku et al. 2003). The soil strength is influenced by the organic matter, water content, soil structure, and texture while the loading is expressed by axle load, number of tyres, tyre dimensions, tyre velocity, and soil tyre interaction (Kirby et al. 1997; Sakai et al. 2008). Axle load should not be confused with axle pressure as axle load is weight of machine.

As Farrakh Nawaz et al. (2012) underlined, if the soil compaction is carried out in steep slopes, this can result in increased runoff and ultimately in increase soil erosion and sediment transport which could be a serious problem for the landscape. Along with the breakdown of soil structure, the process of tillage can also expose bare loose soil which in turn is more susceptible to water or wind erosion than a well-aggregated soil (DEFRA, 2005).

Soane et al. (2012) also reported that, further robust evidence is needed on the environmental and economic aspects of no-till systems under rotation cropping. Finally, HGCA (2014b) emphasised in addition, the importance of field demonstrations in determining the type of tillage options available to farmers.

Table 2.2. Advantages and disadvantages of tillage identified by NSW Agriculture (2000) and Buckingham Frank (1976) and author's compilation.

| Advantages of tillage | Disadvantages of tillage |
|---|---|
| **Physical soil characteristics** | |
| Improved soil aeration and water availability<br>Reduction in soil strength for plants<br>Appropriate soil aggregate size and bulk density to ensure good soil-seed contact<br>Management of soil temperature | Soil compaction<br>Excessive breakdown of soil aggregates |
| **Crop residue and soil water movement** | |
| Management of crop residue<br>Reduced evaporation; increased infiltration<br>Roughen the soil surface<br>Preparing surfaces for operations (i.e. removing ruts)<br>Erosion control | Can cause soil crusting, runoff and erosion |
| **Weed, pest and disease control** | |
| Burying of seeds below germination depth | Bringing of old seeds to soil surface increasing that way weed burden |
| **Chemistry and biology of ecosystem** | |
| Incorporation of surface organic matter into soil<br>Incorporation of fertilisers and herbicides | Reduction in soil organic matter through oxidation and exposure to microorganisms |
| **Economics** | |
| Effect of the above benefits on crop yield | Wasted time<br>Wasted fuel |

## 2.4 Soil physical characteristics and tillage

### 2.4.1 Ensuring that the porosity can provide access to water and air

Successful crop establishment requires the seeds in the soil to have access to water and air (National Soil Research Institute, 2001). Baker et al. (2007) distinguished that the main attribute for successful germination is the availability of both vapour-phase and liquid-phase water.

The capacity of the soil to hold water can be described in terms of its porosity, the ratio (in terms of volume) of void to the volume of the soil in situ. The weight of dry soil per volume of soil, namely the bulk density, can be used as a measure of the porosity of a soil, with low values meaning a highly porous soil and vice versa. The volume includes the volume of soil particles and the volume of pores among soil particles and is typically expressed in units of Mg m$^{-3}$ (Equation 2.4). Thus, bulk density reflects the soil's capacity for structural support, water and solute movement, and soil aeration.

$$\text{Bulk density} = \frac{Weight\ of\ dry\ soil}{Volume\ dry\ of\ soil} \qquad \text{Eq. (2.4)}$$

$$\frac{Bulk\ density}{Particle\ density}\ \text{x } 100 = \%\ \text{solid space} \qquad \text{Eq. (2.5)}$$

$$100\% - \%\ \text{solid space} = \text{percent pore space} \qquad \text{Eq. (2.6)}$$

where: $$\text{Particle density} = \frac{Weight\ of\ dry\ soil}{Volume\ of\ soil\ solids} \qquad \text{Eq. (2.7)}$$

Soil particle density is defined as the mass of the solid soil divided by the volume. It differs from bulk density because the volume used does not include pore spaces. Pore size distribution is influenced by the soil's texture but for a given soil texture, reduction in pore sizes will be mainly attributed to potential high bulk density values, which are associated with poor water and air flow which in turn can result in compacted soils (Dexter, 2004). Chaudhari et al. (2013) and the USDA (2008) present the ideal bulk densities values for crop growth for a clay and clay loam soil (Table 2.3). They conclude that values over 1.80, 1.65 and 1.47 Mg m$^{-3}$ restrict root growth for a sansy, silty and clay soil respectively. For both types of soils, bulk densities of below 1.10 Mg m$^{-3}$ were considered ideal.

Table 2.3. General relationship of soil bulk density to root growth based on soil texture (adapted from Chaudhari et al 2013 and USDA 2008)

| Soil texture | Ideal bulk density for plant growth (Mg m$^{-3}$) | Bulk density that restricts root growth (Mg m$^{-3}$) |
|---|---|---|
| Sandy | < 1.60 | > 1.80 |
| Silty | < 1.40 | > 1.65 |
| Clay | < 1.10 | > 1.47 |

Soil compaction can be described in terms of reduction in porosity or void ratio of the soil and increases in bulk density. The large pores which are reduced by compaction processes (e.g. heavy traffic) often provide major infiltration channels through the soil. The potential rate of water intake is therefore a sensitive measure of damage (Davies et al. 2001). Soil compaction causes a hidden degradation of the soil structure that is difficult to locate and rationalize (Mc Garry and Sharp, 2003). It is a complex problem in which machine/soil/crop/weather interactions play an important role and may have economic and environmental consequences for world agriculture (Soane and van Ouwerkerk, 1995).

*Effect of tillage:* Singh & Malhi (2006) reported that bulk density in a loamy Canadian soil was increased under no tillage (1.13-1.58 Mg $m^3$) in their study, but it did not have any detrimental effect on root growth. In a similar study Logsdon & Karlen (2004) reported that switching to no tillage and changing from continuous corn to either a 2- or 6-year rotation did not negatively impact bulk densities or crop yields. Continuous macropores probably allowed continual root growth even during transient times of higher bulk density, and the soil was able to recover from these transient high bulk densities due to biological and physical processes.

Recent evidence from Chen et al. (2014) indicated that the soil bulk density at depths 0-200 mm was significantly lower with a mouldboard plough than the no-tillage system while there was no significant effect between these systems in deeper soil (200-300 mm). Van Ouwerkerk & Boone (1970) reported lower total porosity under no-tillage than under tilled conditions for some soils in the Netherlands. By contrast, Jabro et al. (2010) observed no significant difference in soil bulk density between strip-tillage and no tillage systems under barley on a Lihen sandy loam soil in Williston and Blevins et al. (1983) found a similar lack of effect at 0-150 mm between conventional and no tillage for a clay loamy haplaquoll and a loamy hapludoll in Iowa.

Hakansson (2005) explains that compaction affects nearly all soil properties usually in a negative way. Crop yields decrease, time, cost and fuel requirements for tillage operations increase, soil aeration is hampered, denitrification increases and microbial processes are impaired. The cumulative effects of wheel traffic and natural settlement in soils subject to no tillage or shallow tillage over extended periods resulted in a greater degree of compactness during the growing season than in soils which have been ploughed before drilling.

Baker et al. (2007) report that seeds drilled into less favorable no-tillage slots that only provide liquid-phase water for germination, are less likely to germinate. They pointed out that some no-tillage soil openers tend to bend (hair-pin) the last year’s residues into the slot, which causes poor soil to seed contact, interfering this way with seed germination and/or seedling emergence. Gruber et al. (2011) also concluded that high soil disturbance provided slightly more suitable conditions than no-tillage systems for plant germination and growth in both spring and autumn.

### 2.4.2 Ensuring that the penetration resistance does not restrict root growth

Penetration resistance is defined as the resistance of soil to vertical force usually applied by plant roots (Tuzzin de Moraes et al. 2014; Leung et al. 2003). It can be measured using a penetrometer which pushes a metal rod into the soil in order to record the soil’s mechanical strength and is typically expressed in units of MPa. The value of penetration resistance that limits root growth is often assumed to be 2 MPa (Li-Rong et al. 2016; Hamza and Anderson 2005). As for bulk density, optimum penetration values that don’t restrict root growth are given as 1-2 MPa (Bengough and Mullins, 1990). Petelkau (1986) reports that penetration resistance increases in the 0.1-0.8 MPa range can cause a considerable reduction in the rate of root extension. This variability may be related to soil type. Hakansson (2005) reports the critical limit can be relatively high in clay soils with a well-developed macropore system and relatively low in sandy soils with few continuous macropores.

In an analysis of tillage effects on soil physical properties Licht & Al-Kaisi (2005) found that penetration resistance and soil moisture were inversely related throughout the soil profile. Gleadthorpe et al. (2003) stated that poor wheat stands were not due to depletion of the seed reserves, but probably to other characteristics such as coleoptile length, soil surface mechanical resistance, soil moisture content, or as in the case of waterlogged soils, a lack of available oxygen for respiration. Charman and Murphy (2007) reported that variations in soil moisture content with depth can strongly influence penetration resistance profiles and lead to false interpretation of compacted layers. In the same study they reported that precise interpretation of penetration resistance measurements can be difficult because plant roots behave in different ways than metal rods and they may find less direct but easier paths through soil.

*Effect of tillage:* A number of studies have found that non-inversion tillage led to higher penetration resistances than conventional tillage systems (Crittenden et al. 2015; Kurothe et al. 2014). The results from Çelik et al. (2011) agree with the findings of the above studies, in which the penetration resistance of three layers (11- 20 cm, 21-30 cm and 31-45 cm) were highest under no-tillage and reduced tillage, and the lowest values of penetration resistance were obtained in conventional tillage systems after maize harvest in Adana, Turkey.

By contrast the study by Kahlon et al. (2013) showed the positive effect of no tillage and residue mulch in enhancing soil physical properties. They reported higher penetration resistance and lower infiltration and saturated hydraulic conductivity under conventional than no-tillage along with mulch application. Licht & Al-Kaisi (2005) also reported that the penetration resistance of strip-tillage was often comparable with no-tillage, but greater than chisel plough in the upper layers (0-20 cm) of the soil profile.

Finally, a similar study of tillage effects on penetration resistance in a barley-oat-wheat system was carried out in Manitoba by Wang et al. (2009). It was concluded that the direct drilling system resulted in lower or comparable soil penetration resistance with similar soil moisture contents, compared to the conventional tillage system. In the same experiment it was shown that subsoiling practice proved to be more effective in reducing soil penetration resistance and controlling weeds than the conventional tillage.

### 2.4.3 Ensuring that the soil aggregation maximizes soil-seed contact

Soil texture ranges from fine clay particles (< 0.002 mm diameter) to silt (0.002 - 0.05 mm diameter) and sand (> 0.05 mm diameter). However depending on a range of factors, sand, silt, and clay particles are typically arranged into secondary particles called peds, or aggregates (Foth 1990; National Soil Research Institute 2001), and this arrangement forms the "structure" of the soil.

Aggregates are formed through the combination of mineral particles with organic and inorganic substances (Figure 2.2). Aggregates occur in a variety of forms and sizes. These are often grouped by size: macro- aggregates (>250 μm) and microaggregates (20-250 μm) with these groups being further divided by size (Hoorman et al. 2009; Tisdall & Oades 1982).

Different size groups differ in properties such as binding agents, and carbon and nitrogen (N) distribution (Bronick and Lal, 2005) as a result of the interaction of many factors. These include the environment, soil management factors, plant influences and soil properties such as mineral composition, texture, organic carbon concentration, pedogenic processes, microbial activities, exchangeable ions, nutrient reserves, and moisture availability (Kay et al. 1998).

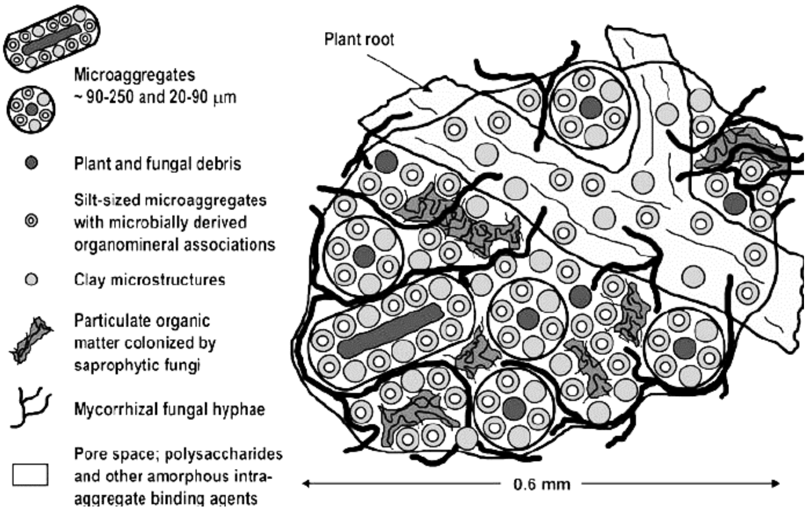


Figure 2.2. Schematic illustration of a soil aggregate (after Jastrow and Miller 1997)

Kay (1990) defined three aspects of the dynamics of soil structure: the soil structural form, the soil structural stability, and the soil structural resilience. The ability of soil to fulfil a function, at any given time, is determined by characteristics of structural form. USDA (2011) uses the term aggregate stability as “a measure of the proportion of the aggregates in a soil which do not easily slake, crumble or disintegrate”. A low aggregate stability can be associated with an increased risk of soil erosion by wind and water. Andrews et al. (1996) considered aggregate stability as a useful soil physical property (indicator) for determining soil quality under productivity and environment goals. Soil quality is defined by SSSA (2008) “the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health”. Soil aggregate stability is a good indicator of soil structure determined by the rearrangement, flocculation and cementation of particles (Bronick & Lal 2005; Six et al. 2000; Duiker & Rhoton 2003). It is mediated by soil organic carbon, biota, ionic bridging, and clay and carbonates content. The organic carbon acts as a binding agent and as a nucleus in the formation of aggregates. Biota and their organic products contribute to the development of soil structure and have the potential to restructure it, which in turn exerts a significant control over carbon dynamics (Ritz & Young 2011; Bronick & Lal 2005).

Lastly soil structural resilience refers to the capacity of aggregates to restructure following natural fracturing processes (e.g. when clay shrinks and swells) and cultivation. Together, the terms resilience and resistance describe the ability of a soil system to cope with external disturbances or stresses (Arthur et al. 2012), including different intensities of tillage. Hayes (2013) underlined that the closer the percentage of stable aggregates is to 100 %, the better the soil's structure will be while adopting a conservation tillage system.

*Effect of tillage:* Daraghmeh et al. (2009) showed that compared to conventional tillage, reduced tillage improved soil structure through a combination of increased soil organic matter, reduced soil bulk density and increased proportion of larger aggregates (2-6.3 mm).

In a relevant study, Paul et al. (2013) concluded that at 0–15 cm soil depth, amounts of macro-aggregates were consistently greater under reduced tillage as compared to conventional tillage. Roldán et al. (2007) also concluded that soil aggregation was greater under no tillage concomitant with greater organic carbon than under a mouldboard plough in Mexico. By contrast Mbagwu & Bazzoffi (1989) could not pick up any significant differences in macro-aggregates between minimum and conventionally tilled plots. However they reported that the potential of dry aggregates to disintegrate upon contact with water was greatest in the conventionally tilled and least in the untilled treatments.

## 2.5 Crop residue and soil water movement

Soil surface characteristics can affect crop yields and be affected by tillage through changes in the level of crop residues, evaporation suppression and temperature, and changes in water infiltration.

### 2.5.1 Crop residue

Crop residues, in general, are parts of the plants left in the field after crops have been harvested and threshed or left after pastures are grazed. These materials have at times been regarded as waste materials that require disposal, but there is an increasing realisation that they are important natural resources (Kumar and Goh, 2000). Turmel et al. (2015) in a system analysis described that the benefits of residue retention are regionally variable and depend on both agro-climatic and socioeconomic factors. They pointed out that there are positive effects of retaining crop residues on the soil surface which can improve soil structure by: (1) increasing soil aggregation through adding organic matter to the top soil, (2) protecting soil aggregates from raindrop impact, and (3) protecting soil from compaction caused by raindrop impact. However Tivy (1990) reported that crop residues alone can replace only a small fraction of the organic carbon lost from intensive tillage. Sun et al. (2015) in a meta-analysis showed that no-tillage can significantly reduce runoff because of the higher residue retained compared to both reduce tillage and mouldboard plough. It has also been widely recognised that residue cover can increase water infiltration (Blanco-Canqui et al. 2009; Leys et al. 2010; Kurothe et al. 2014). Zhang et al. (2016) in a similar study attributed the high water and soil losses for treatment without surface residue to the increased soil erodibility with hardening of the soil surface caused by rain impact in the absence of ground cover. In brief, without the protective benefits of vegetative or residue cover, bare soil is subjected to the direct impact and erosive forces of raindrops that dislodge soil particles. Dislodged soil particles fill in and block surface pores, contributing to the development of surface crusts that restrict water movement into the soil (USDA, 2008). Cushioning the force of falling raindrops with crop residues can help reduce the number of soil particles dislodged, giving the soil time to absorb the rain.

*Effect of tillage*: Tillage intensity and implements’ geometry of the drilling equipment also play a role in whether the residue is cut, incorporated or left on the soil surface (Moitzi et al. 2014). Inversion tillage buries most of the crop residue and leaves the soil surface almost totally bare, by contrast no tillage drilling leaves almost all of the residue on the soil surface (Rasnake, 1983).

The study of Choudhury et al. (2014) identified that residue retention/incorporation in non-inversion tillage systems caused a significant increase of 15.6% in total water stable aggregates at the surface soil (0–15 cm) and 7.5% in sub-surface soil (15–30 cm), which indicated that residue management could double water stable aggregates as compared to the other treatments without residue retention/incorporation.

Similar research conducted by Kahlon et al. (2013) has also shown that long term addition of crop residue and more decomposition of organic matter under non-inversion tillage favor an increase in both carbon and nitrogen concentration in the soil. On the other hand residue can also favour bacterial communities (Navarro-Noya et al. 2013). The continuous inputs of organic material in the treatments with residue serve as a C source for energy and cell synthesis. Souza et al. (2016) in a study carried out in Brazil showed that crop residues left on the soil surface under non-inversion tillage systems also reduced evaporation.

### 2.5.2 Evaporation suppression and temperature

In dry environments, crop yields can be limited by the availability of water. The rate and quantity of evaporation from the soil surface is a complicated process affected by many soil characteristics (including tillage effects on soil) and environmental interactions (Lal and Shukla, 2004). In semiarid regions with high evaporative demand relative to seasonal precipitation, maintaining adequate surface residue is often difficult due to limited residue production and rapid residue decomposition rates (Schwartz, Baumhardt and Evett, 2010).

Under such conditions, residue cover even under no tillage may decline to less than 30% during fallow periods (Lampurlanés and Cantero-Martínez, 2006) resulting in near bare soil conditions. The presence of crop residues with non-inversion tillage systems keeps the soil cooler and wetter than bare ploughed soil (HGCA, 2012). Figure 2.3 from FAO clearly depicts the effect the residue cover on evaporation for different soil types.

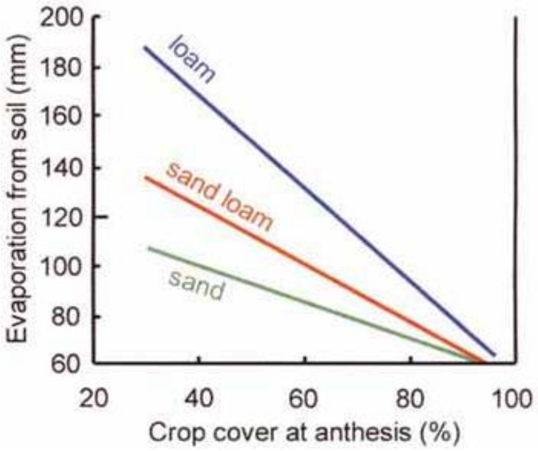


Figure 2.3. Season evaporation from the soil surface for three soil types as related to percent crop cover at anthesis *(adapted from Food and Agriculturae Organization of the United Nations (2016))*

*Effect of tillage*: Under conservation tillage, more plant residues on the soil surface reduces evaporation giving higher water content in the topsoil, which has been linked to lower soil temperatures (Rasmussen, 1999). This is supported by Su et al. (2007) who reported a lower evapotranspiration (ET) in no tillage and strip tillage plots as compared to conventional tilled plots. They attributed this to greater and deeper soil water storage as extensive tillage usually exposes the soil surface to water loss and evaporation. Soil cover with crop residues not only reduces evaporation but mitigates the risks of soil erosion significantly, an aspect of paramount importance under Mediterranean rainfed agriculture (García-Ruiz 2010; Delgado et al. 2013). Although tillage systems have little or no effect on air temperature they can be used to increase or decrease soil temperatures (Wall and Stobbe, 1984). Depending on the tillage system, the crop residue left on the soil surface insulates the soil from the sun’s energy during the day. In the summer residue can protect the soil from solar insolation / heat (cooler soil) but in the winter residues can insulate the soil from cold temperatures (warmer soil). This means the seasonal range of soil temperature is moderated by the residues (Simmons and Nafziger, 2009). The same study also showed that more stored water was usually advantageous in dry summer periods, but could be a disadvantage at drilling time and during early growth (i.e. in the wetter autumn and winter periods), especially on soils with poor internal drainage. They also found that in northern Illinois, crops need more water than the rainfall supplies after the crop canopy closes. Soil moisture saved through reduced tillage systems may be important in years with below-normal rainfall. Excessive soil moisture in the spring months often reduces corn growth because it slows soil warming and may delay drilling. However, on soils where drought stress often occurs during summer months, additional stored moisture leads to higher yields.

### 2.5.3 Water infiltration

Another aspect in which tillage can help the successful establishment of a new crop is by encouraging the infiltration of water. The infiltration rate is the volume flux of water entering through a unit soil surface area. The rate of infiltration is controlled by the pore size distribution and the continuity of pores or pathways (Lipiec et al. 2006). If the pore system is significantly reduced in size and continuity or the soil surface is sealed/crusted due to external factors such as soil manipulation (i.e. tillage) and raindrop/irrigation impacts then the rate of water application will exceed the rate of water infiltration into the soil and water will flow over the soil surface as overland flow (Figure 2.4).

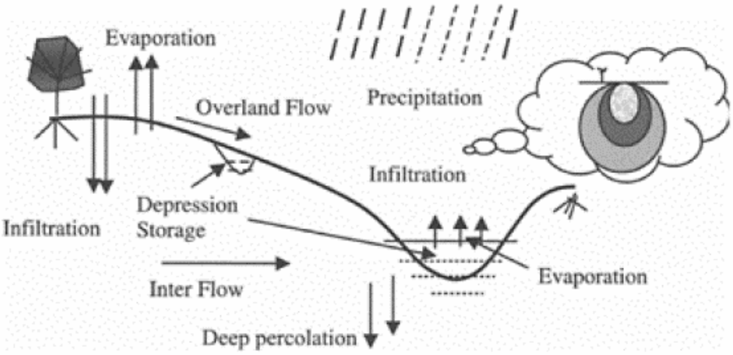


Figure 2.4. A schematic of processes during a rainfall or irrigation event along with the components of hydrological cycle (after Lal & Shukla 2004)

The rate of infiltration in soil varies across soil and climatic conditions and can be influenced by soil texture, i.e. the relative proportions of sand, silt and clay. Clay particles are particularly important as their small size makes them able to fill the voids between larger particles while their charge orientation gives them a crucial role in binding the soil matrix into larger structures (Haghnazari et al. 2015). For a media with a single particle size the water infiltration is approximately proportional to the square of the particle diameter (Iwata, Tabuchi and Warkentin, 1995).

The rate of infiltration is also affected by the initial soil moisture content. In an unsaturated soil, the initial infiltration rate is dominated by the matric potential, which is an inverse function of the moisture content. Hence, the soil hydraulic properties are strongly linked to the water content and its distribution within the soil profile (Haghnazari et al. 2015). As soils become wet, infiltration rate slows to a steady rate based on how fast water can move through the most restrictive layer, such as a compacted layer, or a layer of dense clay.

Soil water content also has a direct impact on the degree of soil cracking which in turn has a large impact on the infiltration function (Mailhol and Gonzalez, 1993). Cracking occurs within many clay soils, where they shrink excessively on drying. During irrigation, these cracks serve as macro-pores through which water can quickly enter the soil.

In their review of factors affecting infiltration of agricultural soils, Haghnazari et al. (2015) emphasized the role of soil structure. The infiltration rate was particularly affected by the average pore size, distribution of pore sizes and connectivity of pores. Soils with a good structure and high porosity generally have the highest rates of water infiltration (Charman and Murphy, 2007).

*Effect of tillage*: In some studies, water infiltration was higher in tilled soil than no-tilled soil (Erbach et al. 1992; Ferreras et al. 2000). However, Alamouti & Navabzadeh (2007) reported that deep tillage resulted in greater water infiltration rates than semi-deep and shallow tillage systems. By contrast Topaloğlu (1999) found that tillage practices had no significant effect on infiltration rates in sandy loam and clay loam soils. Jabro et al. (2016) also reported that zero tillage, shallow tillage (100 mm) and deep tillage (300 mm) methods did not significantly affect soil infiltration rates in a sandy loam with the porosity being similar in the three tillage practices.

Ruqin et al. (2013) reported a decreasing trend of infiltration rates and infiltration amount with increasing tillage intensity: 8-year no tillage (2009) > 6-year no tillage (2007) > mouldboard plough. A similar study by He et al. (2009) also demonstrated that the infiltration rate in a 0-15 cm soil layer for no-tillage was 7.6% higher than that for conventional tillage but this difference was not significant. In the 15-30 cm soil layer, however, the mean infiltration rate was 249% greater than conventional tillage, and this treatment difference was significant.

### 2.5.4 Surface runoff and erosion

Erosion attributed to soil management can be distinguished as either tillage or water erosion. Tillage erosion is defined by the Soil Science Society of America as the downslope displacement of soil through the action of tillage (Lindstrom, 2002). Water erosion is the soil displacement due to the action of water. The rate of water erosion depends on the climate, soil, topography, plant cover and land use (Charman and Murphy, 2007). There are 4-phases involved in the erosion process: i) detachment, ii) entrainment, iii) transport and iv) deposition (Lal, 2010). The first involves the detachment of soil particles from soil aggregates and the second, the transport of these particles together with other entrained particles away from their original position. Both these processes require energy. Lipiec et al. (2006) concluded that infiltration of water increases water storage for plants and groundwater recharge, and reduces surface runoff generation and soil erosion.

With regard to water erosion, Elliot (1994) reports that raindrop impact on bare soil can detach soil particles from aggregates and runoff can transport these particles, and existing entrained soil particles, to another location. As the rainfall/irrigation impact, partially separate soil aggregates, and especially aggregates which are not water stable, can cause surface sealing or crusting as the loose soil particles fill the surface pores. This in turn leads to decreased water infiltration and increased runoff, which in turn increase soil transport and hence increased soil erosion.

Adequate residue on the soil surface is necessary to protect soil from rainfall or irrigation impacts. When residue decomposes, voids are created in the soil surface that provide vertical flow pathways for percolation. Fungi, bacteria, and other decomposers produce a biochemical residue that acts as glue and forms stable aggregates, or tiny clumps of soil, that are resistant to slaking. If surface organic matter is not present aggregates cannot form, or will be weak and break apart. Small particles of mineral soil are then able to move with water (Heckrath et al. 2005). As Kohler et al. (2017) pointed out, the action of fungal hyphae alone is able to enhance soil aggregate stability. Their study also highlighted that the involvement of fungal hyphae in the formation and stabilization of soil aggregates can be related directly to the hyphal entanglement of loose soil particles and secretion of organic substances that act as glues.

*Effect of tillage*: Reductions in soil erosion rates as a result of conversion from conventional to low disturbance tillage systems are well documented (Lindstrom, 2002; Mal & Hesse, 2015; Singh & Kaur, 2012). Wang et al. (2016) also showed that tillage induced erosion may create an accelerating mechanism of water erosion, and a decrease in tillage intensity can efficiently reduce soil and water losses in hilly areas (Figure 2.5). Intensive water erosion caused by modifying soil structure after tillage can negatively impact water holding capacity, infiltration rate, and levels of soil nutrients and organic matter (Zhang, Nie and Su, 2008). Each of these properties influences soil quality individually as well as their interactions with other factors, making it difficult to assess the impacts of soil erosion on soil quality (Pimentel et al. 1995).

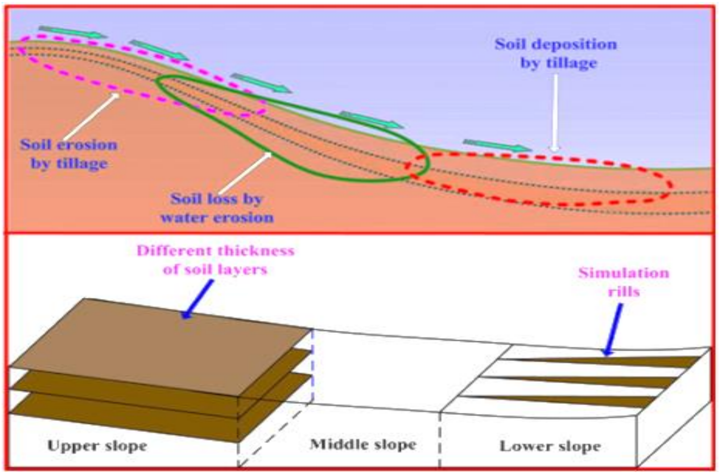


Figure 2.5. Tillage induced water erosion (*after* Wang et al. (2016))

Mhazo et al. (2016) concluded that the runoff coefficient was 41% lower under no-tillage than conventional tillage in plots with mulch cover whereas there were no significant differences between no tillage and conventional tillage in bare soils. Plot management (i.e. soil surface cover, no tillage implementation duration and type of crops grown) had a significant impact on sediment concentration and soil loss response to no tillage.

The above results indicate that crop residue can provide protection of soil against water erosion. For example Baig and Gamache (2009) report that no-tillage farming practices that leave about 80-100 % crop residues on the surface protect the soil from raindrops and wind and hence reduce erosion. With increased straw residues, water is more likely to infiltrate than generate runoff, further protecting the soil against erosion.

## 2.6 Weed control

One potential benefit of tillage is to minimize the competition experienced by the crop from “weeds” i.e. “plants growing in the wrong place”. High crop yields depend on the developing crop effectively intercepting light, water and nutrients. The inversion and/or mechanical destruction of existing weeds helps to minimize the competition for such resources.

In UK cereal production, blackgrass *(Alopecurus myosuroides)* is a particularly significant weed. AHDB Cereals & Oilseeds (2016), who describe the key points dealing with its control, conclude that blackgrass is an increasing problem because of i) early drilling dates in the autumn and ii) its potential to develop resistance to herbicides. Colbach et al. (2010) summarizing the results of the ALOMYSYS model, reported that the earlier the weed seedlings emerge relative to the crop, the better they survive and tiller. It was also noted that the later the last tillage operation, the more weed seeds have germinated already and thus are killed by the tillage. Moss (2013) at Rothamsted Research, summarized that herbicide-resistant populations of blackgrass have been confirmed in England and are increasing in France and Germany. Herbicide resistance is inherited and occurs through selection of plants that survive herbicide treatment. With repeated selection, resistant plants multiply until they dominate the population. He also pointed out that blackgrass can seriously reduce crop yields through competition for nutrients, especially nitrogen. Chauvel et al. (2001) posited that the existence of cross-resistance mechanisms observed within resistant biotypes dramatically reduced the number of efficient herbicides and therefore the use of non-chemical, cultivation practices is also required. The study conducted by Chauvel et al. (2001) indicated the economic advantages of crop rotations (such as including peas in cereal and oilseed rape production) to improve weed control. In a different study, Colbach and Sache (2001) examined the dispersal of blackgrass and identified four factors that had a significant effect on seed dispersal. The most important was wind speed which increased both the number of dispersed seeds and the dispersal distance with the highest seed density. The location also influenced these two parameters, and it appeared that both the number of collected seeds and the distance at which seeds were dispersed were higher in the downwind direction. Moss and Lutman (2013) summarized the major blackgrass control methods available in winter cereals and the levels of control that can be achieved, based on a recent comprehensive review of over 50 field experiments (Figure 2.6). These included ploughing, delayed drilling, higher seed rates of the main crop, competitive main crop varieties and herbicides. When the methods are combined, the overall blackgrass reduction could reach 99%.

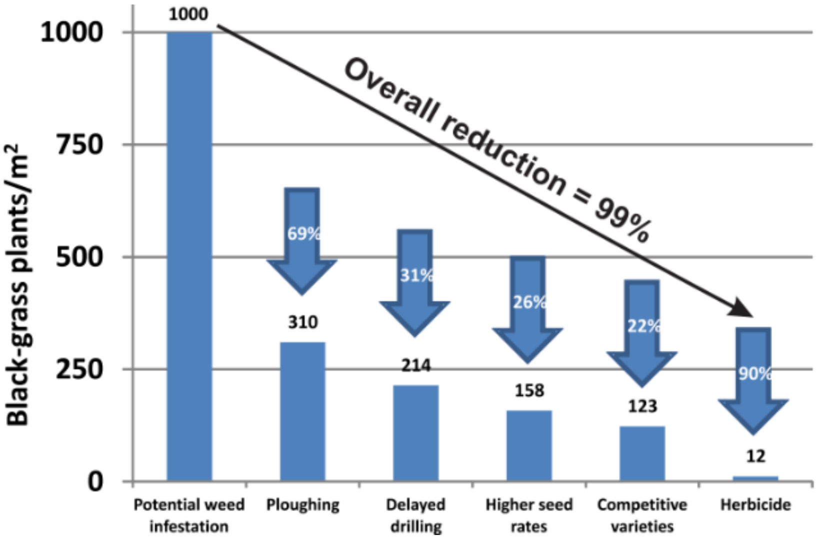


Figure 2.6. Potential benefit of integrating use of several non-chemical methods with herbicides (After Moss & Lutman (2013))

Finally, Farooq (2015) indicated that the effect of primary tillage on weeds is mainly related to the type of implement used and to tillage depth, concluding that weed densities in non-inversion tillage systems are generally higher than in plough-based systems. Thus, with conservation tillage systems, a much higher level of management is required, due to these increased weed problems (Elliot, 1994).

## 2.7 Chemistry and biology of the soil-crop ecosystem

### 2.7.1 Soil organic matter

Soil organic matter is the material in a soil which is directly derived from plant and animal residues, root exudates, living and dead microorganisms, and soil biota. Decomposition of residues results in the release of sugars, cellulose, lignin, waxes and organic acids all of which contain the element, carbon (Jones et al. 2010). Some of the features of organic matter and their impacts on soils as documented by Barbagiannis

(2010) are presented in Table 2.4. As already discussed, an increase in organic carbon can help maintain the stability of aggregates during rainstorms. Soane and van Ouwerkerk (1995) also report that higher organic matter content and greater biological activity in the topsoil can lead to a more favourable arrangement of soil particles (structure) for crop growth.

Table 2.4. Organic matter characteristics and their impacts on soil

| **Feature** | **Comments** | **Impact on soil** |
|---|---|---|
| Colour | The dark brownish-gray color soils is due to organic substance | Greater light absorption resulting in faster warming |
| Water retention | Organic matter retains water up to 20 times its weight | Prevent swelling and shrinkage, water retention in sandy soils |
| Reaction with clay | Formation of stable aggregates | Improving structure, aeration and water permeability |
| Solubility in water | Small | Small losses by leaching |
| pH | Regulates the pH | Maintains a constant pH |
| Cation exchange capacity | The CEC of humic substances range 300-1.400 meq / 100g | Increases CEC, 20-70% due to organic matter |
| Decomposition | Release of $NH_4^+$, $NO_3^-$, $PO_4^{3-}$ | Source of nutrients for plants |

Soil organic carbon (SOC) is the carbon (C) stored in soil organic matter (SOM). According to Soil Association Scotland (2009), the optimum soil organic carbon value for the UK is around 3%. Kay & VandenBygaart (2002) concluded that stratification of soil organic matter begins soon after soils are converted from conventional to no tillage with increases in the top 5 cm of the soil profile and losses at depth.

The balance between gains near the surface and losses at depth may vary with time; some data of the above study suggested gains near the surface might persist longer than losses at depth. As the intensity of cultivation increases, the amount of ground cover and associated root contributions decreases, so that the quality and quantity of soil organic carbon decreases as well (Lal, 1998). Changes in soil organic carbon are generally slow and difficult to measure against the large background carbon content in arable soils.

*Effect of tillage*: Iowa State University (2005) reported that no-tillage can increase soil organic matter by as much as 1 ton acre$^{-1}$ year$^{-1}$. The same study underlined that combining cropping systems and conservation tillage practices, such as no-tillage, strip-tillage or ridge-tillage, are proven to be very effective in improving soil organic matter and soil quality. Greenland (1980) also concluded that the use of conservation tillage practices (for example zone tillage or no-till) can also increase soil carbon. In similar research Parihar et al. (2016) showed that the soil carbon content in no tillage plots was 35% higher than that in conventional tilled plots for soil depths of 0-15 and 15-30 cm.

Figure 2.7 illustrates that after a three year experiment, no-tillage had a higher soil carbon content compared to other tillage systems with a different intensity in the top 150 mm of the soil (Iowa State University 2005). Intensive tillage systems stimulate the degradation of soil organic matter compared to perpetual vegetation which favors organic carbon to accumulate (Figure 2.8). This is consistent with Gupta et al. (2014) who also showed that residue retention and no tillage regimes had the highest capability to hold the organic carbon in the soil surface with the highest stratification ratio of soil organic carbon.

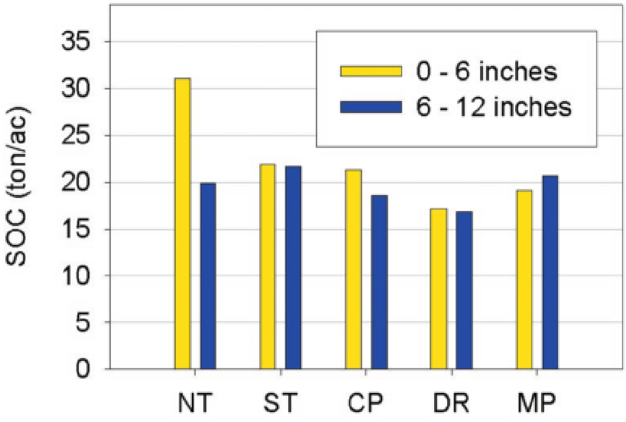


Figure 2.7. Soil organic carbon for no-tillage (NT), strip tillage (ST), chisel plough (CP), deep rip (DR) and moldboard plough (MP) at two depth increments (*after Al-kaisi & Yin 2005*)

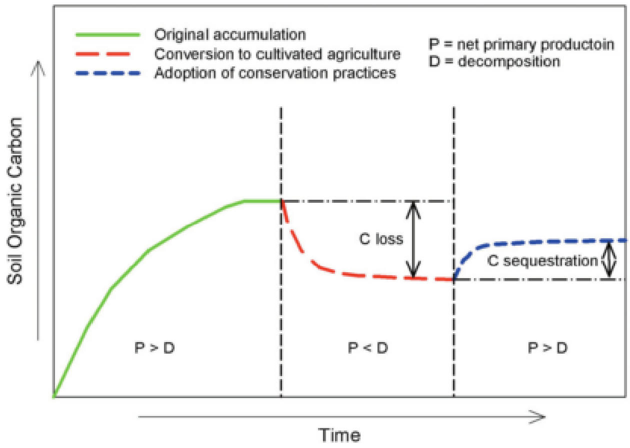


Figure 2.8. Schematic illustration of soil organic carbon in relationship to time as affected by different agricultural systems (*after Iowa State University 2005*).

The above findings are also supported by Huang et al. (2015) who found that a combination of no-tillage (NT) with organic fertilizer can increase macro-aggregate formation and improve soil physical properties at the soil surface. This was attributed to decreased soil disturbance and the addition of crop residues or manure. The positive effects of conventional tillage (CT) on soil organic carbon in deeper soils were attributed to crop root development in deeper soil layers. Jégou et al. (1997) in addition pointed out that, earthworms' burrow construction is important in organic carbon transfer in the soil because their walls were litter carbon enriched to a degree which varied with species and soil depth.

Chatskikh et al. (2008) reported that soil tillage intensity can affect both crop growth and soil carbon (C) and nitrogen (N) turnover and balances, including emissions of greenhouse gases (GHG) such as $CO_2$ and $N_2O$. The same study concluded that compared with conventional tillage (CT), non-inversion tillage treatments decreased greenhouse gas emissions by 0.56 (reduced tillage, RT) and 1.84 (direct drilling, DD) Mg $CO_2$-eq. $ha^{-1}$ $year^{-1}$. Charman and Murphy (2007) have argued that practices involving enhancement of vegetative cover, such as low disturbance tillage systems, improved pasture systems and agroforestry could have a large effect in reducing greenhouse gases through the sequestering of carbon from the atmosphere into the form of soil organic matter.

### 2.7.2 Nitrogen availability and crop growth

Most of the nitrogen (N) in the environment is in an unavailable form for plant uptake. Nitrogen in the plant root zone is either nitrogen gas ($N_2$), as a component of the air occupying the soil pore spaces, or organic N present in various forms in the soil organic matter, including plant and microbial proteins and amino acids, (Deenik 2006).

Leary et al. (2014) from University of Minnesota reported that nitrogen, present or added to the soil is subject to several changes (transformations) that dictate the availability of N to plants and influence the potential movement of $NO_3^-$-N to water supplies. In brief and to understand better the nitrogen paths in soils, its transformations are briefly described below (Leary et al. 2014; Johnson et al. 2005; Deenik 2006):

*Mineralisation*: in N mineralization, the organic N contained in soil organic matter is converted into plant-available inorganic ammonium, ($NH_4^+$), as a result of the activities of soil microorganisms. Because it is a biological process, rates of mineralization vary with soil temperature, moisture and the amount of oxygen in the soil (aeration) (Johnson et al. 2005).

$$\underset{\textit{organic N}}{R - NH_2} \dashrightarrow \underset{\textit{ammonia}}{NH_3} \dashrightarrow \underset{\textit{ammonium}}{NH_4^+}$$

*Nitrification* is the process where ammonium is further changed by microorganisms to the inorganic nitrate form ($NO_3^-$), also available to plants. The rate at which nitrogen becomes available is determined by the complexity and stability of the organic matter and by microbial activity. It may occur in days or, if the nitrogen is in a very stable form, it may take years (Frate and Advisor, 2007).

$$\underset{\textit{ammonium}}{NH_4^+} \dashrightarrow \underset{\textit{nitrite}}{NO_2^-} \dashrightarrow \underset{\textit{nitrate}}{NO_3^-}$$

*Denitrification* occurs when N is lost through the conversion of nitrate to gaseous forms of N, such as nitric oxide, nitrous oxide and dinitrogen gas. This occurs when the soil is saturated and the bacteria use nitrate as an oxygen source. De-nitrification is therefore common in poorly drained soils (Johnson et al. 2005).

$NO_3^-$ --> $NO_2^-$ --> $NO$ --> $N_2O$ --> $N_2$

*Nitrate* *nitrite* *nitric* *nitrous* *dinitrogen*

*oxide* *oxide gas*

*Immobilization* is the reverse of mineralization. All living things require N; therefore microorganisms in the soil compete with crops for nitrogen. Immobilization refers to the process in which nitrate and ammonium are taken up by soil organisms and therefore becomes unavailable to crops. Johnson et al. (2005) in Cornell University explained that incorporation of materials with a high carbon to nitrogen ratio (e.g. straw), will increase biological activity and cause a greater demand for N, and thus result in N immobilization. Immobilization only temporarily locks up N. When the microorganisms die, the organic N contained in their cells is converted by mineralization and nitrification to plant available nitrate.

$NH_4^+$ *and/or* $NO_3^-$ --> $R - NH_2$

*ammonium* *nitrate* *organic N*

When soil microorganisms consume organic matter, $CO_2$ is released. If the organic material contains more nutrients (N, P, K) than the organisms need for their own biomass growth, the excess is released to soil solution (Purakayastha et al 2009). Thus, as mentioned previously, poor water infiltration can result in soil solution runoff, which in turn depletes soil fertility, and pollutes the environment through eutrophication and groundwater contamination (Singh and Kaur, 2012)

Retaining an optimum range of available nitrogen in soils is a complex procedure. Nitrogen should be released to plants and at the same time not been lost through runoff. Any losses of nitrogen will depend on rainfall intensity, soil cover and the soil's physical condition (Patil et al. 2010; Breland and Hansesn, 1996). Taking into account all the above, tillage practices that deplete surface residue can also reduce soil microorganisms and organic carbon which in turn can affect the rates of mineralization and finally the nitrogen availability to plants. Net mineralization of nitrogen after soil disturbance is greater in fine, rather than coarse-textured, soils probably due to release of more previously protected organic matter (Jackson et al. 2003; Hassink 1992). Plant available nitrogen helps maintain soil organic carbon because it promotes plant growth and consequently results in more plant residue and roots (Barber, 1979).

*Effect of tillage:* Abid & Lal (2008) showed that no-tillage soil had pronounced stratification of organic carbon and nitrogen concentrations and pools, with high values limited to the surface layer when compared to tilled soils. This was explained by the different working depths and intensities of tillage systems compared. Nitrification activity is generally higher with no-tillage and reduced tillage compared with conventional tillage systems probably because the changes in soil physical properties and improved water relations (IPNI, 2012).

Dikgwatlhe et al. (2014) have shown that rapid decrease in carbon and nitrogen stocks occurred when residues were removed under mouldboard plough. Therefore, crop residue retention, either by soil incorporation or surface placement, is critical regardless of the tillage intensity. In another study by Mu et al. (2016) showed that the return of crop residues retained higher moisture for reducing penetration resistance and promoting crop root growth, provided more nitrogen, and thus increased crop grain yield. Lastly Alijani et al. (2012) showed that complete residue removal is to be avoided due to concerns of reduced soil organic matter levels and environmental and soil erosion problems. Instead, incorporation of appropriate rates of corn residues (7500–15,000 kg ha$^{-1}$) is recommended to increase soil organic carbon in a wheat–corn–wheat rotation.

### 2.7.3 Soil biology

Soil micro-organisms, which are critical to soil health, live in the microscale (1-100 μm) environments within and between soil particles (Raynaud et al. 2014; Pedersen et al 2015). Differences over short distances in pH, moisture, pore size, and the types of food available, create a broad range of habitats. Micro-organisms affect soil structure and therefore water availability and risk of soil erosion. They can protect crops from pests and diseases. They are central to organic matter decomposition and nutrient cycling, and therefore affect plant growth and amounts of pollutants in the environment. The role of soil biology in provisioning and regulating services provided by soil ecosystems is illustrated in Table 2.5.

Table 2.5. Soil biology and its role in delivering ecosystem services (adopted from Dominati et al. (2010))

| Services | Role of biology |
|---|---|
| Physical support | Critical to soil aggregation, improved soil structure making soil more habitable for plants. |
| Nutrient cycling | The activities of soil bacteria, archaea and fungi drive nutrient cycling in soils and are involved in weathering minerals. |
| Buffering water flows | Soil macropores are formed by plant roots, earthworms and other soil biota, which may depend on soil microbes as food or for nutrients. |
| Biological control of pests and pathogens | Soil is habitat to beneficial species that regulate the composition of communities and thus prevent proliferation of herbivores and pathogens. |
| Carbon storage and regulation of greenhouse gas emissions | By mineralising soil carbon and nutrients, microbes are major determinants of the carbon storage capacity of soils. Denitrifying bacteria and fungi and methane producing and consuming bacteria regulate nitrous oxide ($N_2O$) and methane ($CH_4$ ) emissions from soils. |

Schjønning et al. (2004) and Mele & Crowley (2008) concluded that microbial biomass carbon and earthworm density/species were the best soil biological indicators of soil quality. Clapperton & Ryan (2002) reported that creating a soil habitat is the first step to managing soil biological properties for long-term soil quality and productivity.

This means using soil management practices that reduce soil disturbance, managing weeds and disease with crop rotations and mixed cropping, and using high quality compost and composted manure. In the same study it was underlined that, for instance, unstructured soils with low organic matter content that have fine aggregates or clay within the plough layer will take between 3-5 years to build the soil biological properties necessary to improve soil structure and stability depending on climate and previous soil management.

#### *2.7.3.1 Microbial biomass carbon*

Microbial biomass in soil is the living component of soil organic matter. The microbial population is composed of protozoa, algae, fungi, actinomycetes, bacteria and viruses, and these components contribute to the maintenance and productivity of agro ecosystems (Titi 2003). Carbon contained within the microbial biomass is stored energy for microbial processes. Therefore, microbial biomass carbon may indicate potential microbial activity (Wright et al. 2005). Titi (2003) also reported that the changes in the microbial and total carbon $C_{mic}$:$C_{org}$ relationship reflect the pattern of organic matter amendments to soils.

Soil organisms respond sensitively to soil management practices and climate. Soil management and tillage in particular, affects the quality of habitats for a variety of living organisms, which is expressed in species richness and biodiversity of the soil system. These are well correlated with beneficial soil and ecosystem functions including water storage, decomposition and nutrient cycling, detoxification of toxicants, and suppression of noxious and pathogenic organisms (Doran and Zeiss, 2000). Existing research indicates that the higher the amount of soil organic carbon and soil aggregates, the higher the value of microbial biomass carbon (Zhang et al. 2014; Nyamadzawo et al. 2009).

Over the long term, frequently-tilled soils undergo losses in soil organic matter and microbial activity, increases in net nitrate production and deterioration of soil structure (Jackson et al. 2003). Govaerts et al. (2007) stated that it is the retention of crop residue that increases microbial biomass and micro-flora activity, and that the continuous, uniform supply of carbon from crop residues serves as an energy source for microorganisms. Higher microbial activity implies greater temporary immobilisation of carbon and other nutrients, and consequently smaller losses of nutrients from the soil-plant system.

*Effect of tillage:* Parihar et al. (2016) in a long term study demonstrated that zero tillage led to significant improvement in soil biological health as indicated by the change in microbial biomass carbon. In a similar study, Nyamadzawo et al. (2009) concluded that improved fallow systems increased soil microbial biomass carbon, aggregate-protected carbon, mineralizable carbon, organic matter associated with different soil fractions and soil aggregation when compared to natural fallow or continuous maize. In addition, these properties were maintained during the cropping phase. Wright et al. (2005) also reported that tillage regimes that promote the maintenance of crop residues at the soil surface had beneficial impacts on soil fertility through enhancement of soil microbial biomass and supply of mineralizable nutrients.

Surveys such as that conducted by Kabiri et al. (2016) have shown that firstly low soil disturbance under medium-term reduced tillage practices affects positively soil microbial properties, which may improve soil functioning and quality in semi-arid environments and secondly soil microbial attributes can be useful indicators of tillage-induced changes in soil quality. Thirdly adopting reduced tillage systems with less soil disturbance and a moderate addition of crop residues, particularly leguminous species, restored the microbial indicators of soil quality in semi-arid agroecosystems with low organic matter contents.

#### 2.7.3.2 Earthworms

Studies have shown that the importance of soil earthworms in improving soil porosity and aeration by making both horizontal and vertical burrows, some of which can be very deep in soils (Bhadauria and Saxena, 2010). Earthworms also decompose soil organic matter and release nutrients to soil solutes (Singh and Kaur, 2012), and can mix soil layers and incorporate organic matter into the soil. They are associated with greater levels of bacteria and fungi activity (Eriksen-Hamel et al. 2009). Thus, if there are no organic substances or food available on the surface, the population of earthworms is likely to decline.

Luise et al. (2013) concluded that earthworm abundance was positively correlated with both total species richness and number of species collected per sample, indicating that when more earthworms were collected, there was a higher probability of collecting more species too. Therefore, farms with higher earthworm abundance also tended to have higher species richness.

Ploughing disrupts earthworm soil habitats, especially deep burrowing (anecic) species, and exposes earthworms to predation and desiccation (Holland, 2004). Lubbers et al. (2017) has recently related the feeding behaviour of earthworms to their burrowing activities; epigeic, anecic and endogeic earthworms incorporate fresh organic matter into aggregates in different ways which may have important consequences for the protection of carbon and long term soil organic carbon storage (Bossuyt, Six and Hendrix, 2006).

*Effect of tillage:* Ernst et al. (2009) suggested that earthworm biomass and species richness were generally higher in plough-less tillage systems, whereas few differences were found between reduced tillage systems. They pointed out that the conversion of formerly conventional tillage into reduced or conservation tillage will change soil organic carbon distribution in the topsoil and will positively affect earthworm biomass and biodiversity, and thus might be important to sustain soil conservation and crop production. According to Chan's (2001) review of the tillage impacts on earthworm population, abundance and diversity, different species of earthworm respond differently to tillage. It was concluded that while the abundance of the deep burrowing species (anecic) tends to decline under tillage, particularly under deep ploughing, endogeic species can actually increase in number especially when there is increased food supply. In the short term, the increase of anecic species in no-tillage systems has no effect on soil porosity and no-tillage soils can be more compacted than ploughed soils (Chan's 2001; Peigné et al. 2009). It has also been shown that a long-term experiment is usually required to assess the effect of biological activity on the physical components of soil in farming.

Yvan et al. (2012) reported that in silty soils earthworms contribute significantly to soil regeneration after compaction. After severe compaction, the number of macropores increased due to earthworm activity in the highly compacted volumes but it took more than two years for full recovery of burrow systems. The infiltration rate, which was almost zero after compaction, increased quickly after several months but it also took two years for it to fully recover.

## 2.8 Tillage and economic costs

Economic performance can be assessed in terms of financial profitability to the farmer, but also in terms of the economic value of the farming system as a whole to society. The financial profitability may ignore some environmental effects because these costs are not directly borne by the farmer in monetary terms. Financial feasibility and financial return are two key issues that farmers and land owners consider when deciding between alternative land uses (Graves et al. 2011). Financial and economic analyses are typically undertaken using marginal cost-benefit analysis (CBA) where the benefits and costs of a project are compared to a default or counterfactual situation.

The financial viability of various farm enterprises, and particularly crop production, is usually heavily dependent on farm equipment and labour costs. Another closely-related factor is the work rate of the equipment, which largely determines the labour costs. Furthermore, the work rate of a piece of farm equipment to undertake a particular operation is usually closely associated with the investment cost of the equipment (Elliot, 1994).

Mahdi & Hanna (2008) underlined that one of the anticipated benefits of conservation tillage is the reduced cost of tillage operations. Firstly, because of the reduced number of machinery passes, so that two or more activities to be combined into one, and secondly it permits the use of machines with lower draught requirements.

Adoption of conservation tillage on the farm depends on the assumption that it will maximize net farm income and/or reduce risk taking. However, producers who switch to conservation tillage may see an increase in capital costs. The amount of investment depends on the existing machinery complement (Baig and Gamache, 2009).

### 2.8.1 Costs and benefits per annum

Crop production costs are typically related to either a unit of production or a cost per hectare.  They can divided into three main forms: variable costs, assignable fixed costs, and fixed costs (Graves et al. 2005).  Variable costs usually refer to the cost of seed, fertilizer and agrochemicals which increase proportionally with the area of cropping. Assignable fixed costs typically include machinery and labour costs. The level of fixed costs is assumed to be relatively constant (over the short term) and include costs such as farm administration, insurance, and farmstead costs (Vozka, O ’dogherty and Godwin, 2006). Farm revenues are derived from farm income and sales of capital items. Gross margin is the value of revenues minus variable costs and it is usually expressed on a ‘per hectare’ basis. Finally profit, or net farm income, is the difference between revenue (value of marketed output) and all the costs. Factors that contribute to the net farm income include yield, cost of inputs used in crop production (labour, fuel, fertilizer, pesticide, seeds and machinery), and expected output (commodities) prices.

One of the key factors that reflect the farm’s income, as mentioned above, is the expected yield of the harvested crop per unit area. There are contradicting literature studies indicating that low disturbance and non-inversion tillage systems can result in the same or even higher crop yields (Wang et al. 2015; Toliver et al. 2012) when compared to conventional tillage systems. Others conclude that conventional tillage systems are related with higher yields (Koch et al. 2009; JI et al. 2015). Assuming no statistical yield difference between tillage systems, the cost of the equipment and its work rate will shape the final benefits. The work rate will define the number of passes in the field which will determine how often the equipment is used. This in turn will influence the cost of fuel required, the cost of repairs due to wear and the expected equipment’s working life.

### 2.8.2 Energy requirements

The increased land area that can be covered by a single piece of equipment can allow for better time regulation (and cost) of operations, as farmers seek to improve soil health whilst reducing machinery and labour costs. Soil tillage, especially ploughing is one of the most energy consuming processes in plant cropping (Tayel, Shaaban and Mansour, 2015). The intensity of soil tillage depends on the number of soil tillage operations, kind of tillage (active, driven by the power-take-off (PTO) on a tractor, or passive by drawbar power), implement geometry and depth of operation (Loibl 2006; Godwin 2007). Fuel consumption of soil tillage is correlated with intensity of soil tillage (Moitzi et al. 2013).

Implement geometry refers to its width and rake angle. In general, as reported by Godwin (2013), implements with rake angles up to 45° demand less draught than implements with angles greater than 50°. Minimising the draught force is not always the main issue: Godwin & Spoor (1984) reported that reducing the magnitude of the specific resistance (draught force / cross section area of soil disturbance) is a better indicator of overall tillage efficiency than the draught itself. They concluded that winged caused greater soil disturbance than non-winged tines.

According to Spoor & Godwin (1978) at shallow working depths the soil is displaced forwards, side- ways and upwards (crescent failure), failing along well defined rupture planes at angles of approximately 45$^{o}$ to the horizontal. Crescent failure continues with increasing working depth until, at a certain depth, the critical depth, the soil at the tine base begins to flow forwards and sideways only (lateral failure) creating compaction at depth. The same study reported that non-winged tines at deep working conditions, tend to lose energy due to the reason of lateral failure causing sideway compaction.

Tractors are the basic power unit in crop production. As reported by Mileusnić et al. (2010), the optimum tractor-machinery system depends on parameters like soil conditions, farm area and fuel consumption, with a particular focus on fuel economy. Based on the required forces to pull any implement, and for a given area and working depth and speed, losses of energy while drilling, also include wheel slippage. To eliminate slippage the weight of the tractor, the equipment width, and tyre inflation pressure and condition should be adjusted correctly, not only to save energy/fuel but also to eliminate compaction (Dickson & Sullivan 1997; Inns & Kilgour 1978; Catchment sensitive farming 2011). In summary, working depth, width, rake angle, operation speed, number of passes, tyre inflation pressure and condition will all have an impact on fuel requirements. The selection of tillage system has a direct effect on production and profitability. Lower-cost establishment, combined with minimum pass husbandry can provide cost advantages compared to inversion tillage systems (Knight 2003).

## 2.9 Critical review of missing aspects

The review of the literature describing results on yield, soil and profitability resulting from different tillage systems, reveals that a wide variety of studies were carried out in the past. However, the above results focus primarily on their individual effects on i) specific soil properties or ii) on crop parameters, or iii) on profitability or iv) on a combination of two effects (i.e. soil + crop yield). More specific, the majority of the studies examine the effect of tillage systems on i.e. crop yield, NDVI, soil organic carbon, nutrients cycling, soil compaction and the role that crop residue has on different soil properties. Hernanz et al. (2014) compared the effect of three tillage systems on crop production and energy use efficiency within a rainfed-wheat monoculture in semi-arid Spain. Parvin et al. (2017) did study the effect of mouldboard ploughing and shallow tillage on sub-soil physical properties and crop performance while Martínez et al. (2016) in two decades of no-till experiment researched the crop yield, soil organic carbon and nutrient distribution in the soil profile. However, there is a lack of information on an integrated assessment of the agronomic, environmental and economic performance of different types of conservation tillage systems in crop rotations involving autumn sown wheat and oilseed rape in the UK. In addition there is also a need for studying longer term tillage systems-weeds interaction over i.e. a 5-10 year period. The present study, over a period of three years, will assess the effect of conservation tillage systems i) on soil condition (i.e. physical, chemical and biological properties), ii) on crop growth and yield (i.e. yield, crop residue, NDVI) and iii) on farm profitability along with monitoring energy use efficiency (i.e. net margin, energy and fuel requirements) in a wheat-oilseed rotation in UK. After monitoring all the parameters which are included within each of the study's objectives, the strategic objective will identify how the configuration and use of the examined systems can be optimised. This in turn will help farmers and government in regards to the selection of such conservation tillage systems, because at the end of the Thesis their key strengths and weaknesses will be highlighted.

# 3 METHODOLOGY: SITE AND TREATMENTS

This section describes the field site, the treatments applied in the experiment, which parameters have been measured and a comprehensive explanation of how the measurements were carried out.

## 3.1 Field site

Lamport Hall Estate (52°35'85"N 0.87°25'63"W) is situated about 14 km north of Northampton in United Kingdom. The Estate includes a country house and gardens but it is surrounded by arable and grazing land. Half of the Estate has been placed in Higher Level Stewardship scheme with much of the remaining area managed commercially as an arable enterprise. In association with the local land agents called Berrys, Lamport Hall also allows Frontier Agriculture to run a series of experiments and trials on their land.

### 3.1.1 Climatic parameters

The annual rainfall in the area was 598, 702, 530 and 559 mm and the minimum and maximum ranges of temperatures were 6.0-13.4 °C, 7.3-14.9 °C, 6.7-14.5 °C and 7.6-14.4 °C for 2013, 2014, 2015 and 2016 respectively (Figure 3.1 and Figure 3.2). The mean annual rainfall between 1981 and 2010 at the area was 658 mm and the mean maximum and mean minimum for the same years were 14.2 °C and 6.2 °C respectively (Pitsford, 2017).

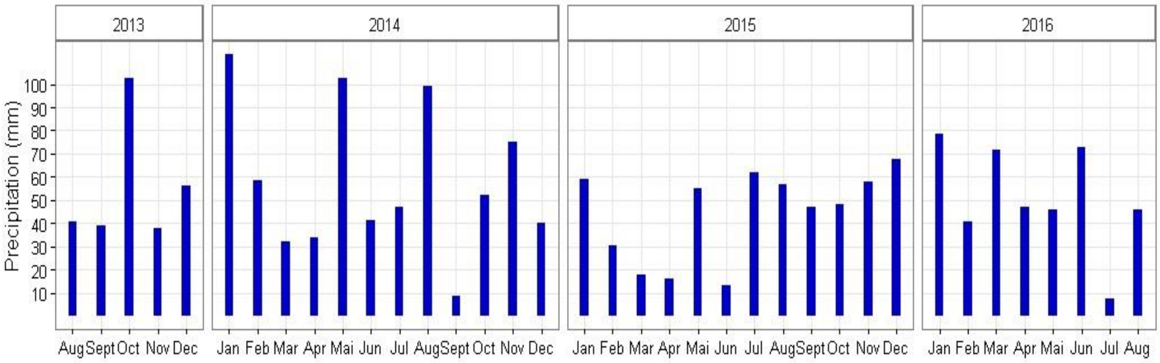


Figure 3.1. Monthly precipitation (mm) from August 2013 to August 2016 (*data from Pitsford weather station*)

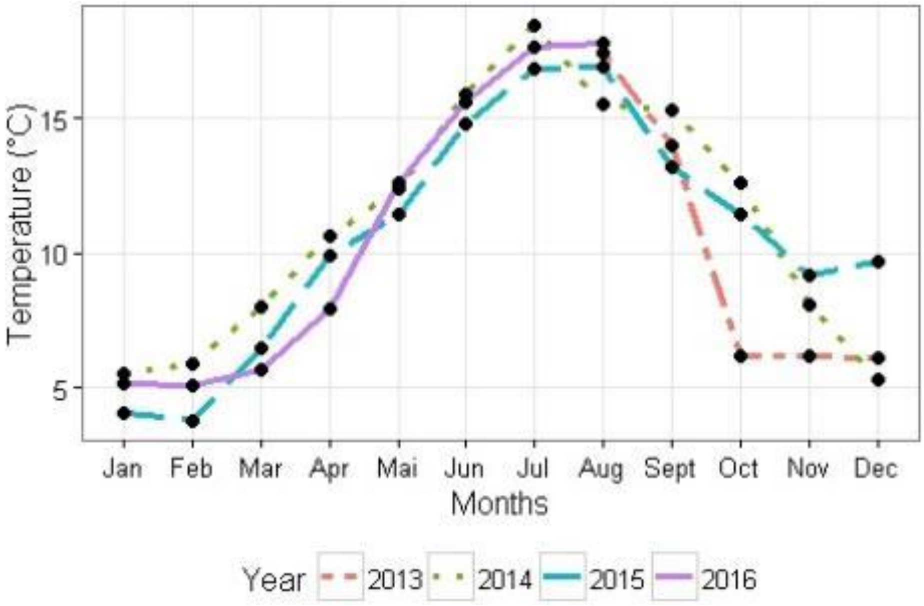


Figure 3.2. Mean monthly temperature (°C) from August 2013 to August 2016 (*data from Pitsford weather station*)

In the East Midlands of England, tillage operations for oilseed rape and winter wheat take place in August and September respectively. In the first year 2013 there was 41 mm of rainfall in August and 39 mm in September. August 2014 was wetter, while September within the same year was drier than 2013. Last's year rainfall in August was almost half of that in 2014 and September rain reached 47 mm (Table 3.1). As in terms of temperature, differences between years for August and September were not great; however the coldest month was September 2015 and the warmest August 2013.

Table 3.1. Average rainfall and temperature for August and September in 2013, 2014 and 2015

| | 2013 | | 2014 | | 2015 | |
|---|---|---|---|---|---|---|
| | Rainfall (mm) | Temp (°C) | Rainfall (mm) | Temp (°C) | Rainfall (mm) | Temp (°C) |
| August | 40.6 | 17.4 | 98.9 | 15.5 | 56.8 | 16.9 |
| September | 39.0 | 14.0 | 8.5 | 15.3 | 47.2 | 13.2 |

### 3.1.2 Selection of fields and their soil type

The experiment was undertaken in two joining fields: Top Furze (TF) is a square-shaped field red marked and Snagsborough is an "L-shaped" field purple marked both 4 ha in size (Figure 3.3).

Figure 3.3. Aerial snapshot of the experimental fields at Lamport, (after Google 2016)

The predominant soil of the two fields belongs to the Banbury series with a small proportion of Top Furze belonging to the Denchworth series (National Soil Resources Institute, 2008). The Banbury series is described as well-drained, fine and coarse loamy, ferruginous soils over ironstone. Some are deep, fine loams over clayey soils with slowly permeable subsoils and slight seasonal waterlogging. The Denchworth series are described as seasonally-waterlogged, slowly-permeable soils. A laboratory analysis of soil texture was also carried out by the sieving and sedimentation method on 14 samples for Snagsborough and 10 for Top Furze. The sampling was carried out at 100 mm depth and randomly on zones of similar soil texture as indicated by electrical conductivity survey from SOYL Ltd (Appendix A). Cranfield's laboratory analysis showed that the soil in Top Furze has a clay texture and that in Snagsborough has a clay to clay loam texture (Figure 3.4).

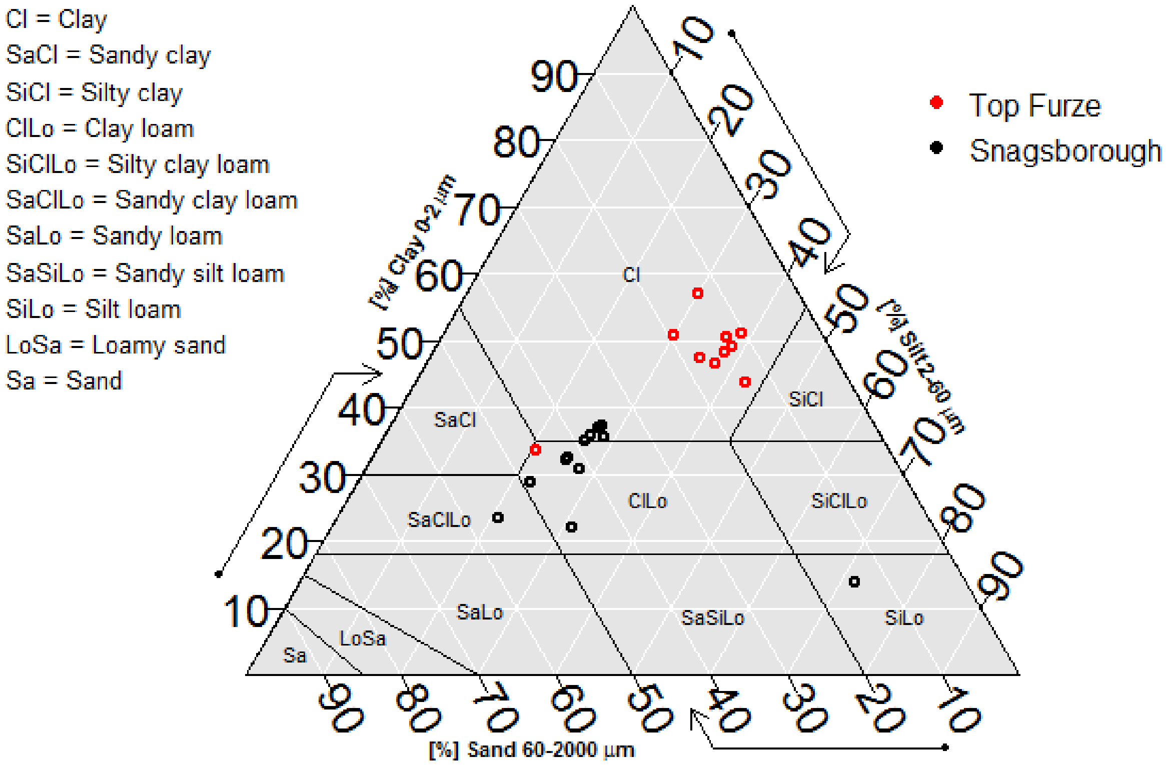


Figure 3.4. Soil textural descriptions of the study fields, Lamport Hall estate

## 3.2 Tillage treatments

The experiment included five tillage treatments. The default or “control” system was the existing farm system and the other four systems comprised different single-pass tillage equipment. Some of the tillage treatments were trailed and some mounted. Mounted refers to treatments that are bolted or clamped to a tractor and trailed to treatments drawn behind it.

### 3.2.1 The Farm system

The Farm system varies between the drilling of wheat and the drilling of oilseed rape. In the wheat, a ‘two pass’ system is used which comprises a Sumo Trio cultivator and a Kuhn HR 4002 combi-drill (power harrow + drill combination). By contrast with the oilseed rape, the farm system is a ‘single pass’ system which includes the Sumo Trio cultivator with a seed hopper attached (Table 3.2).

Table 3.2. The control farm system treatment comprises a two-pass system with wheat and a one pass system with oilseed rape

| Crop | Wheat | Oilseed rape |
|---|---|---|
| Tillage system | Two-pass tillage system comprising Sumo Trio and Kuhn HR 4002 drill | One-pass tillage system comprising Sumo Trio with seed hopper attached |

The Sumo Trio comprises (as its name suggests) three parts (Figure 3.5). It is a 3 m wide tractor-mounted system which comprises 6 rows of tines with a distance of 500 mm between rows. The first components are subsoiler legs mounted in a staggered pattern on a toolbar which can be adjusted to a maximum depth of 400 mm via metal pins.

The second component is a double row of 500 mm diameter concave discs, mounted in pairs on independently suspended arms. Finally there is a 609 mm x 10 mm tube fitted with notched cutting/drive rings which has a total diameter of 800 mm. The rings have a convex shape adjacent to the barrel, creating soil consolidation and cracking.

Legend
1: Disc assembly
2: Packer assembly
3: Scraper assembly
4: Leg assembly
5: Point assembly
6.Active soil retainer
7.Disc depth control
8.Lights
9 & 10.Main frame

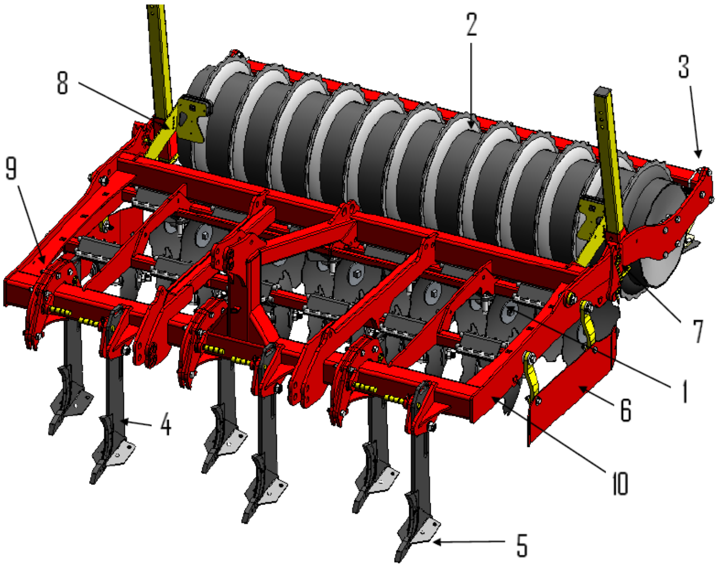


Figure 3.5. Schematic illustration of Sumo Trio (After Sumo UK Ltd)

The Kuhn HR 4002 seed drill (Figure 3.6) is connected to the power take-off of the tractor. It is a 4 m wide, mounted combi-drill. The first component is 32 tines spaced 125 mm apart which loosen the soil at 100 mm depth. The second component is 13 horizontally mounted “stirrers” that rotate and distribute the residue across the soil surface. This is followed by bar harrows which chop the residue and mix it with the surface soil, and then 32 pneumatic coulters that deliver the seed. The last components are spring tines which re-level the soil surface after seed placement.

Figure 3.6. The farm system - Sumo Trio (used only in rape with the seed hopper; left) and Kuhn HR 4002 (plus Sumo Trio without the use of seed hopper used in wheat; right)

### 3.2.2 Sumo Deep Tillage Seeder (DTS): Single pass drill

The first conservation tillage treatment is the Sumo DTS (Figure 3.7; Figure 3.8). This is a 4 m wide trailed strip tillage system. The first components are 12 leading opener discs spaced 330 mm apart which help to clear the crop residue from the previous season. They loosen and prepare a band of soil where the seed is to be placed and leaves the soil in between the rows undisturbed. The next two parts of the Sumo DTS are tungsten-edged deep loosening legs which loosen the soil which is followed by seed coulters which place the seed in the strip. This is then followed by covering discs which channel loosened soil over the seed and pneumatic press wheels which firm the soil around the seed and also govern the drilling depth of the coulters.

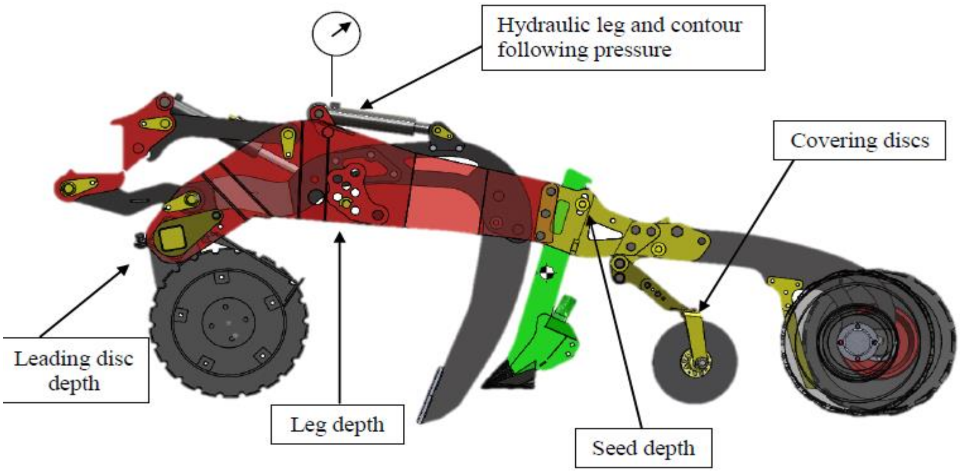


Figure 3.7. Schematic illustration of Sumo DTS main operating parts (After Sumo UK Ltd)

Figure 3.8. Field treatment of the Sumo Deep Tillage Seeder

### 3.2.3 Claydon Hybrid Drill: Single pass drill

The second conservation tillage treatment is the Claydon Hybrid Drill. This is a 6 m wide, mounted implement which includes 19 seed coulters spaced 300 mm apart. It follows the strip tillage principle in that the leading tine is followed directly in-line by the seeding tine (Figure 3.9; Figure 3.10). There are four main parts: 1) Depth wheels, 2) leading tine loosening the soil, 3) the release seeding tines (coulters) which drop the seeds into the strip, and 4) leveling boards which are designed to level the ridges created from the leading tine rather than performing any kind of pressing operation.  These can be replaced with harrow tines if required.

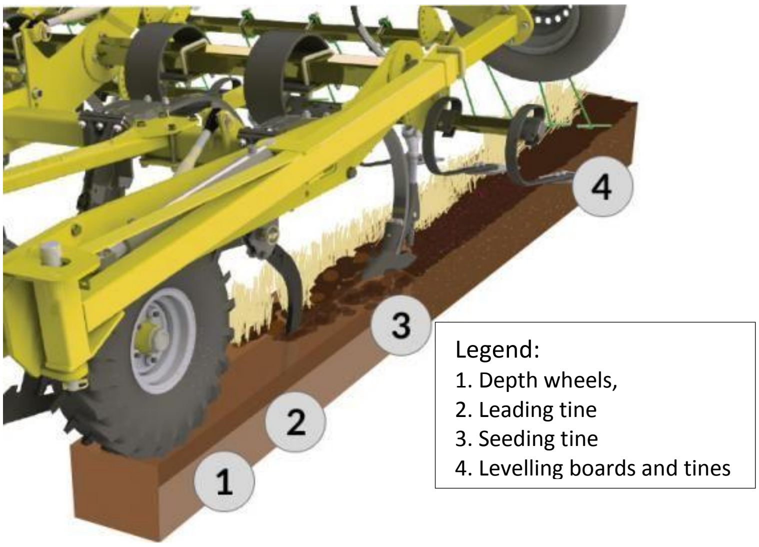


Figure 3.9. Claydon Hybrid Drill consisting parts (After Claydon Yield-o-Meter Ltd)

Figure 3.10. Claydon Hybrid drill at Lamport Hall

### 3.2.4 Mzuri Pro-Til 3T: Single pass drill

The third conservation tillage treatment is the Mzuri Pro-Til 3T which also uses the strip tillage principle. It cultivates the soil and places the seed at a controlled depth. The Mzuri Pro-Til 3T is a 3 m trailed system which comprises 9 seed coulters spaced 333 mm apart (Figure 3.11; Figure 3.12). The operational parts of the Pro-Til begin with 1) a leading tine which loosens the soil, tilling to a depth of 203 mm (i.e. 8 inches), 2) seed metering system, 3) a wheel which follows each leg and consolidates the tilled area (the wheels also carry all the weight of the machine), 4) independent double shoot seeding tines, followed by 5) semi pneumatic reconsolidation wheels, which aim to improve seed - soil contact.

Legend
1.Leading tine
2.Metering system
3.Staggered wheels
4.Seeding tines
5.Semi-pneumaticcoulter wheels

Figure 3.11. Mzuri Pro-Til 3T parts (After Mzuri Ltd)

Figure 3.12. Mzuri Pro–Til 3 at the experimental site

### 3.2.5 Väderstad Rapid A 400S: Single pass drill

The fourth conservation tillage treatment is the Väderstad Rapid. It is a 4 m wide, trailed single pass tillage system which comprises 32 seed coulters spaced 125 mm apart. The key parts of the Väderstad Rapid are illustrated in Figure 3.13 and field operation in Figure 3.14. There are five main processes:

1) Tillage: this consists of two rows of working and slicing discs (410 mm in diameter) that are slightly conical in shape which chop any residue and prepare the seedbed. In addition, a row of cross board tines levels the soil surface.

2) Drilling: the first operational disc is used for fertilizer placement. The following disc is responsible for seed placement. The fertiliser discs with 250 mm spacing place the fertiliser between every second seed row to a preset depth. When the Rapid is used for seeding alone, the fertilizer coulters can be fully raised or they can be used for soil cultivation. The seed disc with 125 mm spacing cuts a small slit under the cultivated soil and places the seed in the soil. Thereafter the seed is covered by soil created by the serrated edges of the discs.

3) Consolidation: each wheel consolidates the soil over two rows of seed and one row of fertiliser. This component is responsible for contact between soil and seed, and therefore water supply to the germinating seed.

4) Loosening: the following harrows create a loose soil surface environment.

Figure 3.13. Main operational parts of Väderstad Rapid (After Väderstad AB)

Figure 3.14. Väderstad Rapid in drilling operation

### 3.2.6 Väderstad SeedHawk 800 C: Single pass drill

The intention was to have a single fourth conservation tillage treatment. However whilst the Rapid can be used to plant wheat, the preferred Väderstad method to plant oilseed rape is a Väderstad Seed Hawk. It is an 8 m wide, trailed no-tillage system which comprises 32 seed coulters spaced 250 mm apart. There are three key parts: the first is a fertilizer tine, this is followed by a seed tine placed on a long coulter arm, and a press wheel which controls the depth of both the fertilizer and the seed tines (Figure 3.15; Figure 3.16).

The narrow fertilizer knives (13.5 mm) cut a slot where the fertilizer is pneumatically placed. The fertilizer depth can be adjusted, but fertilizer is normally placed approximately 20 mm below the seed. The press wheel will close the seed furrow and ensure good seed to soil contact. The depth can easily be adjusted by a pin setting.

The narrow seed knife (13.5 mm) places the seed 35 mm to the side of the fertilizer (Figure 3.15). This separation is important in preventing the fertilizer from burning the seed. The fertilizer knife has a trip mechanism allowing it to fold back when hitting a stone - without affecting the seeding depth of the seed knife.

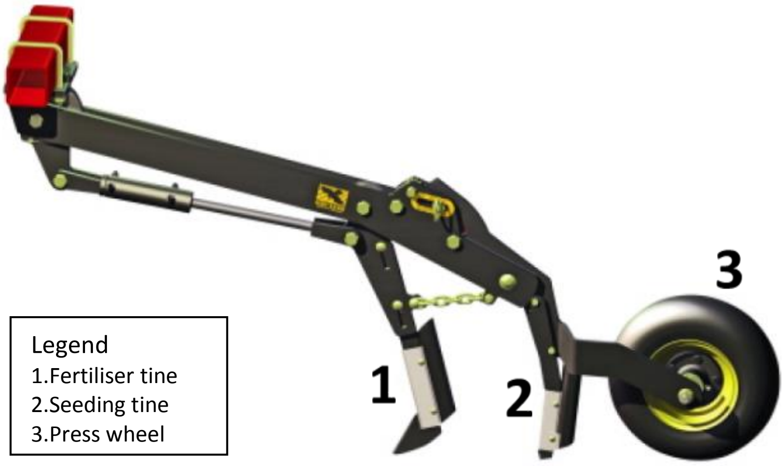


Figure 3.15. Seed Hawk main parts schematic illustration (After Väderstad AB)

Figure 3.16. Väderstad Seed Hawk at Lamport Hall

### 3.2.7 Horsch Sprinter 6ST: Single pass drill

Unfortunately in the second and third year of the experiment, the Väderstad Seed Hawk was not available. Hence an alternative but similar piece of tillage equipment called the Horsch Sprinter 6 ST was selected. This is a trailed 6 m wide strip tillage system, which was used in oilseed rape in the last two cropping seasons of the current study (2014-15 and 2015-16).

Figure 3.17. Horsch Sprinter ST (After Horsch Maschinen GmbH)

It has a tandem tyre packer, which consolidates the seed band. The packing system is aligned in such a way that each tyre follows behind each coulter. The duet coulter prepares the seed bed removing large clods, straw residue and stones from the soil surface so that the seeds can be placed in conditions for optimal growth. The row space is 250 mm, with 3 coulter rows and a total number of 22 coulters (Figure 3.17; Figure 3.18).

Figure 3.18. Horsch Sprinter 6 ST in the experimental field at Lamport

### 3.2.8 Synthesis of treatments

Apart from the Sumo Trio and the Claydon Hybrid which were mounted, each of the other treatments were trailed. All the treatments have tines, but the main working implement, in terms of tillage and its design, differed between treatments. The main working implement in the Sumo Trio, Sumo DTS, Claydon, Mzuri, Väderstad Seed Hawk and Horsch are tines. The Sumo Trio and Mzuri use winged tines while Claydon, Sumo DTS, Väderstad Seed hawk and Horsch use non-winged tines. Väderstad Rapid uses discs for both tillage and seed placement. Seed placement for the rest of the treatments was carried out by seeding tines/coulters. All treatments had press wheels or harrows for consolidation while Sumo Trio had tube fitted rings (Table 3.3).

Table 3.3. Summary of consisting parts of each tillage treatment

| Treatment | Way of Transport | | Main working implement | | | Seed drilling / Fertilizer | | | Consolidation | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mounted | Trailed | Disc | Wheels | Tines | Coulter | Disc | Covering | Wheels | Harrows | Tube fitted rings |
| Sumo Trio | ✓ | | ✓ | | ✓ | ✓ | | | | | ✓ |
| Kuhn HR 4002 | | ✓ | | ✓* | ✓ | ✓ | | | | ✓ | |
| Sumo DTS | | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | | |
| Claydon Hybrid | ✓ | | | | ✓ | ✓ | | | | ✓ | |
| Mzuri Pro-Til 3T | | ✓ | | ✓ | ✓ | ✓ | | | ✓ | ✓ | |
| Väderstad Rapid | | ✓ | ✓x2* | | ✓ | | ✓x2* | | ✓ | ✓ | |
| VäderstadSeedHawk | | ✓ | | | ✓ | ✓ | | | ✓ | | |
| Horsch Sprinter 6 ST | | ✓ | | | ✓ | ✓ | | | ✓ | ✓ | |

✓*: Bar harrow; ✓ x 2*: In strip tillage, two cultivation discs; ✓ x 3*: In seed drilling / fertilizer, three rows of discs (one for fertilizer and two disc rows for seed).

Table 3.4 illustrates the working depth, seed depth and row space of the treatments that have been used in the field study and some technical data adapted from the treatment's official website. Sumo Trio had the deepest operating depth of 200 mm, followed by

Sumo DTS at 177 mm, Claydon and Mzuri at 150 mm, Horsch at 100 mm and finally the Väderstad Rapid and Seed Hawk at 25.4 mm.

The row space was greatest for the Sumo Trio at 500 mm, Sumo DTS and Mzuri had similar row space of 330 mm while both Väderstad Seed Hawk and Horsch had a distance between rows of 250 mm. Finally, Kuhn HR and Väderstad Rapid had the lowest row space of 125 mm. The Väderstad Seed Hawk and Rapid placed the seeds at 12.5 mm and 20 mm depth respectively while the rest of the treatments at 25.4 mm.

Table 3.4. Summary of the specifications of each tillage treatment

| Treatment | Crop | Working width (m) | Working depth (mm) | Seed depth (mm) | Transport width (m) | Row space (mm) | Weight (kg) |
|---|---|---|---|---|---|---|---|
| Sumo trio & drill** | OSR | 3 | 200 | 25.4 | 3 | 500 | |
| Kuhn HR | WW | 4 | 100 | 25.4 | 4 | 125 | 1900 |
| Sumo DTS | OSR&WW | 4 | 177 | 25.4 | 3 | 330 | 2840 |
| Claydon Hybrid | OSR&WW | 6 | 150 | 25.4 | 2.85 | 300 | 2216 |
| Mzuri Pro-Til 3T | OSR&WW | 3 | 150 | 25.4 | 2.95 | 330 | |
| Horsch Spinter 6 ST* | OSR | 6 | 100 | 25.4 | 3 | 250 | 5200 |
| Väderstad Rapid | WW | 4 | 25.4 | 20 | 4.05 | 125 | 3400 |
| Väderstad Seed Hawk | OSR | 8 | 25.4 | 12.5 | 3 | 250 | 6100 |

*Horsch was used in OSR in 2014-15 and 2015-16 because Seed Hawk was not available;

**For the Farm system the Sumo Trio planted the oilseed rape in a single pass while the wheat was planted by the Kuhn HR after the passage of Sumo Trio (two pass treatment

## 3.3 Cropping treatments

An objective of the experiment was to look at the effects of tillage system within a wheat-oilseed rape rotation over three years. In 2012-2013 Snapsborough had been planted with wheat and hence the subsequent crops were winter oilseed rape (2013-2014), winter wheat (2014-2015), and winter oilseed rape (2015-2016). By contrast, in 2012-2013 Top Furze had been planted with oilseed rape and hence the subsequent crops were winter wheat (2013-204), winter oilseed rape (2014-2015), and winter wheat (2015-2016). In the UK, "winter" before a crop is used to indicate that it is planted in the autumn and hence it is in the ground over the winter.

## 3.4 Timing of the tillage treatments per crop

The experiment was completed over three cropping seasons (2013-14; 2014-15 and 2015-16) and the corresponding treatment applications per field and per cropping season are described in Table 3.5. As mentioned earlier whilst the Väderstad Seed Hawk was used on the oilseed rape in the first cropping season (2013-14), it was replaced by the Horsch Sprinter 6 ST in the second and third seasons (2014-15, 2015-16). In the 2015-16 cropping season, the Sumo Trio was used one week before the wheat drilling by the Kuhn HR.

Table 3.5 Dates of treatment applications per field and per cropping season

| Treatment | **Snagsborough** | | | **Top Furze** | | |
|---|---|---|---|---|---|---|
| | 2013 Oilseed rape | 2014 Wheat | 2015 Oilseed rape | 2013 Wheat | 2014 Oilseed rape | 2015 Wheat |
| Farm system (Sumo trio) | 5 Sept | - | 9 Sept d | - | 28 Aug | - |
| Farm system (Sumo trio+ Kuhn HR) | - | 29 Sept | - | 1 Oct | - | Trio: 5 Oct<br>Kuhn: 12 Oct w |
| Sumo DTS | 5 Sept | 29 Sept | 18 Sept w | 23 Sept | 28 Aug | 23 Oct w |
| Claydon Hybrid | 5 Sept | 29 Sept | 8 Sept d | 23 Sept | 28 Aug | 13 Oct w |
| Mzuri Pro Til 3 | 5 Sept | 29 Sept | 18 Sept w | 23 Sept | 28 Aug | 13 Oct w |
| Horsch Sprinter 6ST | - | - | 8 Sept d | - | 28 Aug | - |
| Väderstad Rapid | - | 29 Sept | - | 1 Oct | - | 15 Oct w |
| Väderstad Seed Hawk | 5 Sept | - | - | - | - | - |

*Subscript letters at the 2015-16 season indicate whether the soil was d:dry or w:wet on the drilling day

In the first cropping season, oilseed rape was drilled at the same day for all treatments (5 September 2013) while for the wheat, the Farm system and Väderstad rapid were drilled a week later (1 October 2013). In 2014 for both wheat and oilseed rape, all treatments were drilled on 29 September and 28 August respectively. Finally, in 2015 the oilseed rape was drilled on 8 September for the Claydon and Horsch treatments, on 9 September for the Farm system and on 18 September for Mzuri and Sumo DTS. For the wheat in last season (2015) the Farm system was drilled on 12 September, Mzuri and Claydon on 13 October, the Väderstad Rapid on 15 October and the Sumo DTS 8 days later on 23 October. Table 3.6 illustrates the wheat and oilseed rape varieties and the corresponding seed rates for each cropping season during the experiment. The seed rates were kept the same for all treatments per cropping season. This was accomplished by setting up the metering system on each machinery before drilling in order to have a constant flow of seeds as indicated by the rates applied per season (Table 3.6).

Table 3.6. The variety of oilseed and wheat and the timing of drilling each year

| Season | Crop | Variety | Seed rate (seeds m$^{-2}$) |
|---|---:|---:|---:|
| 2013-14 | Oilseed | Rhino | 50 |
| | Wheat | Relay | 300 |
| 2014-15 | Oilseed | Harper | 50 |
| | Wheat | Leeds | 300 |
| 2015-16 | Oilseed | Extrovert | 50 |
| | Wheat | Reflection | 375 |

## 3.5 Experimental layout and design

As mentioned before, autumn-sown wheat and oilseed rape have been grown for three years alternately in rotation in Snagsborough and in Top Furze (Figure 3.19). Each experimental field comprised four blocks of five treatments; 20 experimental plots in each field which were maintained throughout the three years of the experiment. As mentioned above, the “Farm system” in the wheat field involves a first pass with a Sumo Trio in order for the soil to be cultivated and a second pass with a Kuhn HR 4002 seed drill for the wheat to be planted.

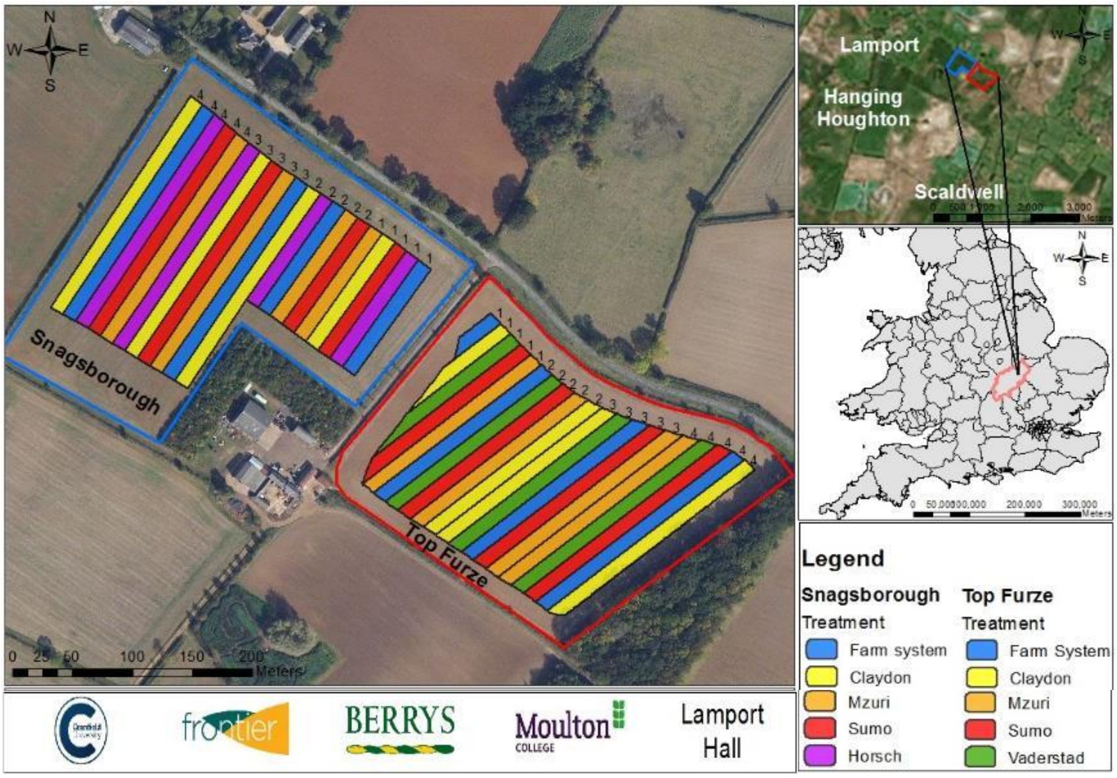


Figure 3.19. Schematic map of the distribution of each treatment for the 2015-16 cropping season (small numbers at the end of the plots indicate number of block).

## 3.6 Methodology: measurements

The research included field measurements of crop and soil characteristics, followed by laboratory analysis and additional controlled experimental work in Cranfield's soil bin facility (which will be described as a separate chapter).

### 3.6.1 Soil sampling methodology

One key research question is: how many samples are needed to pick up a significant treatment effect on various measured properties with a sufficient statistical power. As Crawley (2007) explains, the power of a test is the probability of rejecting the null hypothesis when it is false. This has to do with Type II errors: β is the probability of accepting the null hypothesis when it is false. In an ideal world, β would have obviously been as small as possible (Table 3.7). On the other hand, the smaller we make the probability of committing a Type II error, the greater we make the probability of committing a Type I error, and rejecting the null hypothesis when, in fact, it is correct. Most statisticians work with $\alpha = 0.05$ and $\beta = 0.2$. Now the power of a test is defined as $1 - \beta = 0.8$. This is used to calculate the sample sizes necessary to detect a specified difference when the variance is known (or can be guessed at) (Crawley, 2007). Suppose that for a single sample size, the difference to be detected is *δ* and the variance in the response is $s^2$ (e.g. known from the literature). Then *n* replicates are needed to reject the null hypothesis with the power = 80% (Equation 3.1).

$$n \approx \frac{8 \text{ x } s^2}{\delta^2} \qquad \text{Eq. (3.1)}$$

Table 3.7. Types of statistical errors

| | **H0 is actually:** | |
|---|---|---|
| | **True** | **False** |
| Reject H0 | Type I error | Correct |
| Accept H0 | Correct | Type II error |

In this project, power analysis was conducted using the R statistical language. The soil property chosen to carry out the power analysis was the soil bulk density. This happened for two reasons: i) it is the soil property which best describes the state of soil in terms of its degree of compaction and ii) it will be the most extensively sampled property (twice namely before and shortly after tillage, at 2 depths). The β-value was set to 0.25 thus, for power 75 %, delta δ=0.18, average variance $s^2$ =0.09 (obtained from the literature) and significant difference α=0.05, the number of samples needed per group or treatment is 3.97. Rounding this number, every time, upwards (Xwkru, Zrun and Cohen, 1992) the number of samples needed is 4.

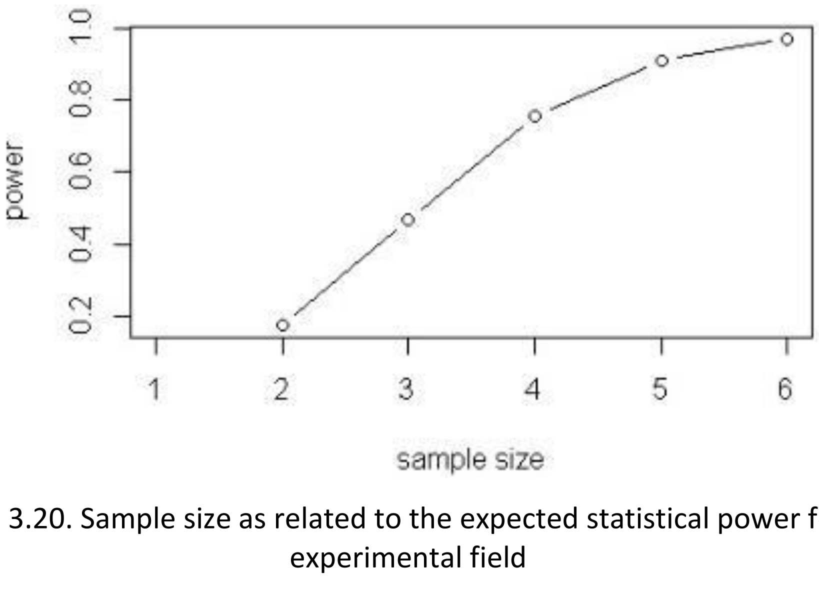


Figure 3.20. Sample size as related to the expected statistical power for the experimental field

For getting a power of 80% or greater, 5 samples per treatment were needed, which was not possible given the study's available resources in terms of time and money (Figure 3.20).

### 3.6.2 Parameters to be measured

The parameters measured in the field can be categorized into those that relate to soil condition, crop performance, and economic profitability (Table 3.8).

Table 3.8. The parameters measured can be categorized into those related to soil condition, crop growth, and profitability

| **Soil condition** | **Crop growth** | **Economic profitability** |
|---|---|---|
| Bulk density (Mg $m^{-3}$) | Annual yield (t $ha^{-1}$) | Annual yield (t $ha^{-1}$) |
| Penetration Resistance (MPa) | Harvest index | Machinery use and cost (£) |
| Total organic carbon (%) | Oilseed rape oil content (%) | Oilseed oil content (%) |
| Earthworms' population | Plant density $m^{-2}$ | Implement applied forces (KN) |
| Microbial biomass carbon (μg $g^{-1}$) | NDVI | Fuel consumption (lt $ha^{-1}$) |
| Water stable aggregates (%) | Black grass density $m^{-2}$ | |
| Hydraulic conductivity (cm $s^{-1}$) | Residue percentage (%) | |
| Available Nitrogen (mg $kg^{-1}$) | | |
| Above ground disturbance (mm) | | |
| Below ground disturbance (mm) | | |

**Soil condition**: Parameters monitored in order to assess soil's condition involved bulk density and penetration resistance (plus moisture content) which will clarify any treatment effects on soil pore space distribution and will emphasize whether a treatment, as mentioned in literature review, did induce or not soil compaction. In addition, soil organic carbon is to change due to management practices like tillage as mentioned in Chapter 2. Some treatments may leave more or less crop residue than others while different treatments will cause dissimilar soil disturbance and organic carbon breakage. More crop residue left on soil surface is directly translated to more food for soil biology alongside increase in their population which means greater amount of organic carbon decomposition. In continue, more soil organic carbon in soil will act as a glue holding soil particles together in form of aggregates. The reason of monitoring the water stable aggregates is in order to assess whether the soil has structural resilience needed so that water and air flow is not hampered. Soil aggregation results in macropores which are brought about by the voids created in the process of aggregation. Hydraulic conductivity was also assessed in order to distinguish how long takes for the water to move downwards through the soil. The greater the time needed for the water to infiltrate, the higher the reduction in soil pore spaces or the higher the amount of pores that are already occupied by water. Finally nitrogen in soil was monitored in order to understand whether there was enough organic nitrogen decomposition through which plant available inorganic nitrogen is formed (mineralization). This will depend on the amount of crop residues and soil biology. Tillage systems that deplete surface residue can also reduce soil microorganisms and organic carbon which in turn can affect the rates of mineralization and finally the nitrogen availability to plants. Cranfield's controlled experiment will assess the amount of above and below ground soil disturbance that the main working implement of each treatment caused.

**Crop performance:** This included parameters that directly and indirectly indicate plant production. Annual grain yield per hectare, the harvest index which is the grain as a proportion of above ground dry mass and the oil content of the oilseed rape all directly signify the performance of each treatment with regards to production. However, parameters such as plant density per unit area, normalized difference vegetation index (NDVI) and black grass infested areas are explanatory parameters or parameters that can indicate or estimate the upcoming yields. The higher the value of plants per meter square or the higher the NDVI early in the season, the higher the predicted yields. On the other hand, if the blackgrass suppression is high then the final expected yields would be lower per unit area as compared to areas with no infestation.

**Profitability:** Profitability parameters included crop marketable yield, machinery use and cost, force requirements to pull the implement through the soil alongside estimated fuel consumption and oilseed oil content.

### 3.6.3 Measurements and sampling

Soil physical properties such as bulk density, resistance to penetration and moisture content have been measured twice each year, a) before drilling and b) immediately after drilling in order to pick up the differences, if any, of the tillage treatment on the soil's structure. Surface residue was also measured immediately after drilling to understand which treatment retained most of the straw residue and relate this to whether the soil properties deteriorate or improve due to the retained residue.

Later in the cropping season, the fields were scanned with The Crop Circle ACS-470 active crop canopy sensor to determine the Normalised Difference Vegetation Index (NDVI) alongside measurements of plant population per $m^2$. Earthworm population per unit area, and water infiltration rate were also measured in each field. Laboratory work included measurements of percentage water stable aggregates, (which is considered to be a good indicator of soil structure), microbial biomass carbon, and available nitrogen.

The majority of the above properties were measured for each cropping season. Organic carbon was measured once in the first cropping season and was measured again at the last cropping season, post tillage operation. Before the end of each cropping season, the areas of blackgrass infestation and the tramlines were digitized using the University's Trimble Geox 6000 GPS unit.

This was accomplished in order to obtain the spatial distribution of the blackgrass infested areas and the tramlines, so that to recognize in which areas the yield was influenced by the above confounding factors. The time it took for a particular treatment to plant an area of known size was also recorded, for the calculation of its work rate (ha $h^{-1}$). The sampling procedure followed the systematic sampling (regular grid). The samples were collected leaving a distance of around 10 m from the plots' ends and sampling every 58 m in the longer plots and every 32 m in the shorter plots whilst at the same time avoiding sampling near to the plots' borders and where visible traffic lanes were present (Figure 3.21). The research study will generate data to test the hypotheses set. The data will focus on crop growth and yield, soil condition, and the economic profitability (Table 3.8). A brief methodology of how each measurement is described in subsequent sections.

Thus, as already shown each field composes of five tillage treatments which are four times replicated giving as mentioned before 20 experimental plots per field. Each plot is sampled 4 times, resulting in a total number of 80 sampling points per field and 160 in total. All parameters monitored, were sampled at the exact same sampling points (Figure 3.21).

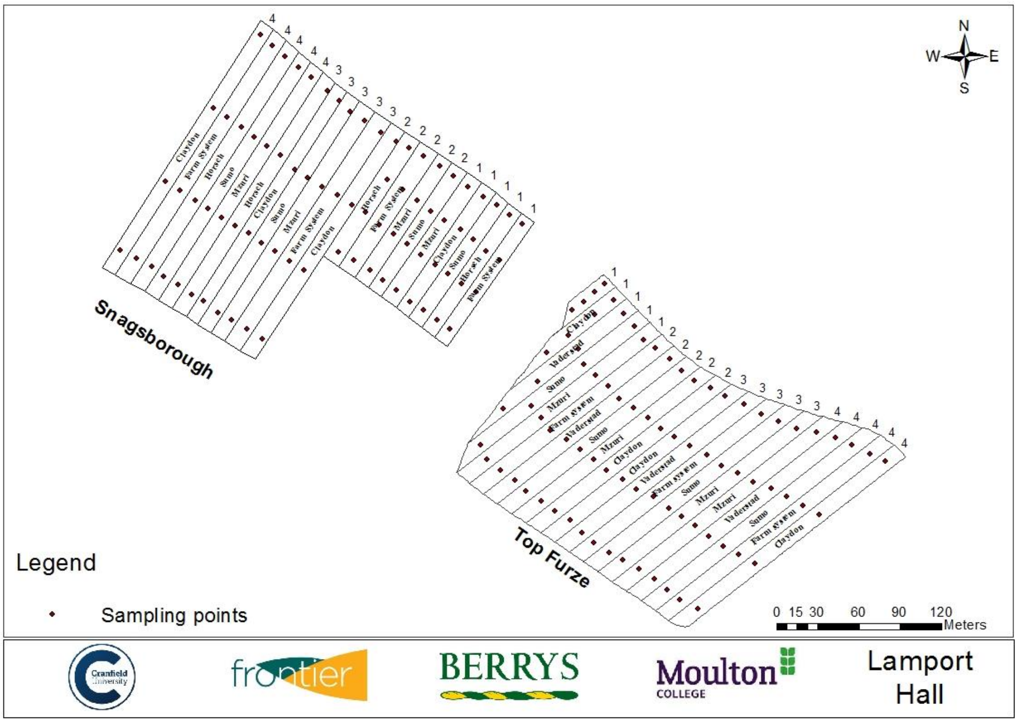


Figure 3.21. Illustration of the sampling locations for both fields

More precisely replicate No 1 indicates the first block of the 5 treatments, No 2 the second batch and so on. The treatments, as mentioned in section 1.4 were randomly allocated within each block. The exact sampling dates varied for each monitored parameter, experimental field and year (Table 3.9; Table 3.10).

Table 3.9. Sampling dates for all the monitored parameters

| Parameter | 2013-14 | | 2014-15 | | 2015-16 | |
|---|---|---|---|---|---|---|
| | SN | TF | SN | TF | SN | TF |
| Bulk density_B | - | - | 12 Sep 14 | - | 22 Aug 15 | 29 Aug 15 |
| Bulk density_A | 18 May 14 | 13 Apr 14 | 11 Oct 14 | 20 Sep 14 | 20 Sep 15 | 24 Oct 15 |
| TOC | 20 Mar 14 | 19 Mar 14 | 21 Mar 15 | 22 Mar 15 | 10 Mar 16 | 11 Mar 16 |
| WSAGG | 20 Mar 14 | 19 Mar 14 | 21 Mar 15 | 22 Mar 15 | 10 Mar 16 | 11 Mar 16 |
| Av.N | 20 Mar 14 | 19 Mar 14 | 21 Mar 15 | 22 Mar 15 | 10 Mar 16 | 11 Mar 16 |
| MBC | 20 Mar 14 | 19 Mar 14 | 21 Mar 15 | 22 Mar 15 | 10 Mar 16 | 11 Mar 16 |
| Worms | - | 15 Jun 14 | 6 Dec 14 | 29 Nov 14 | 26 Nov 15 | 28 Nov 15 |
| Residue | - | - | 9 Oct 14 | 19 Sep 14 | 2 Oct 15 | 23 Sep 15 |
| NDVI | 4 Apr 14 | 4 Apr 14 | 6&29 Mar 15 | 6 Mar 15 | 9 Dec 15 | 9 Dec 15 |
| Blackgrass | - | 21 Jun 14 | - | - | - | 12 Jun 15 |
| Hydr. Cond | - | - | 28 Feb 15 | 24 Jan 15 | - | - |
| Plant counts | 9 Mar 14 | 8 Mar 14 | 19 Nov 14<br>25 Feb 15 | 4 Oct 14 | 2 Oct 15<br>16 Oct 15 | 26 Nov 15<br>18 Jun 16 |

*Bulk density moisture content and penetrometer readings were carried out in the same dates; Bulk density_B: Bulk density before tillage; Bulk density_A: Bulk density after tillage; TOC: Total organic carbon; WSAGG: Water stable aggregates; Av.N: Available nitrogen; MBC: Microbial biomass carbon; SN: Snagsborough; TF: Top Furze

Table 3.10. Timing of sampling along with the exact depths for each soil parameter

| Soil depth (mm) | Parameter measured | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Bulk density (Mg m$^{-3}$) | | Penetration resistance (MPa) | | Moisture content (%) | | Total organic carbon (%) | Water stable aggregates (%) | Available nitrogen (mg kg$^{-1}$) | Microbial biomass carbon (μg g$^{-1}$) | Earth worms (m$^{-2}$) |
| Time* | B | A | B | A | B | A | A | A | A | A | A |
| 0 - 50 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | |
| 0 - 100 | | | ✓ | ✓ | | | | ✓ | | | ✓ |
| 0 - 200 | | | ✓ | ✓ | | | | | | | |
| 150 - 200 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | |

*B: Before tillage; A: After tillage

## 3.7 Soil condition

The soil parameters that have been measured include the soil bulk density, penetration resistance, soil moisture content, total organic carbon, water stable aggregates, earthworms populations, microbial biomass carbon and water infiltration rate (Table 3.8). For all parameters, each field included 80 sampling points per depth and time of measurement within each cropping season (Table 3.9; Table 3.10).

### 3.7.1 Bulk density, moisture content and penetration resistance

Dry bulk density of the soil was measured by taking undisturbed cores (50 mm in diameter and 50 mm deep) from the soil at two depths 0-50 mm and 150-200 mm of each plot avoiding visible areas of traffic. Sampling and analysis for bulk density was carried out twice in the cropping season, i) prior to and ii) immediately after drilling. Hence, there were 160 bulk density samples prior to and the same number of samples immediately after tillage per field (20 plots/4 samples in each/2 sampling depths). The procedure followed was: to put the soil from the field into numbered plastic bags (Figure 3.22), bring all the bags back to the laboratory, weight the numbered empty tins, put the soil of known volume into the tins and record the weight, put all samples at the oven for at least 24 hr at 105 °C and last step take them out of the oven let them cool down and note their oven dry weight.

Figure 3.22. Sampling (left) and lab analysis (right) for bulk density

Alongside with the bulk density (Equation 3.2), the moisture content of each sample was also calculated on an oven dry basis using equation 3.3 where $m_2$: mass of tin + oven dried sample, $m_1$: mass of tin + air dried sample and $m_0$: mass of tin.

$$\text{Bulk density (Mg m}^{-3}\text{)} = \frac{\text{m2}-\text{m0}}{100} \qquad \text{Eq. (3.2)}$$

$$W_{H_2O}\,(\%) = \frac{\text{m1}-\text{m2}}{\text{m2}-\text{m0}}*100 \qquad \text{Eq. (3.3)}$$

Penetration resistance of the soil was measured using the Eijkelkamp digital penetrologger with a push speed of 20 mm $s^{-1}$ into the soil surface, a 30° cone angle, and a basal area of 120 $mm^2$. Penetration resistance was measured three times around each bulk density sampling location and up to a depth of 200 mm from soil surface, giving 240 penetration resistance readings for a single field (Figure 3.23).

Figure 3.23. Penetrometer reading at field site

Measurements at two depths (0-50 mm and 150-200 mm) were chosen due to the reason that it would be interesting in picking up any differences between treatments both on surface level and to soil profile till the depth of the deepest treatment (Table 3.4 ).

### 3.7.2 Total organic carbon

Determination of total organic carbon was carried out at the same depths as with bulk density using the British Standard BS 7755 Section 3.8:1995 *Determination of organic and total carbon after dry combustion (elementary analysis)* which is identical to ISO 10694:1995. Total organic carbon samples were collected after tillage operation at 0-50 and 150-200 mm every March. Because of resources limitations, in terms of money needed for the analysis, measurements were carried out at the first and at the last cropping season and not for the 2nd. Another reason for this, was that changes in organic carbon in soil, as stated in the literature (Chapter 1), need time to appear and do not happen in the short term. Thus, it was more likely to pick up any potential difference in the last rather than in the second cropping season. Total organic carbon results were adjusted for soil bulk density values (section 5.3.4).

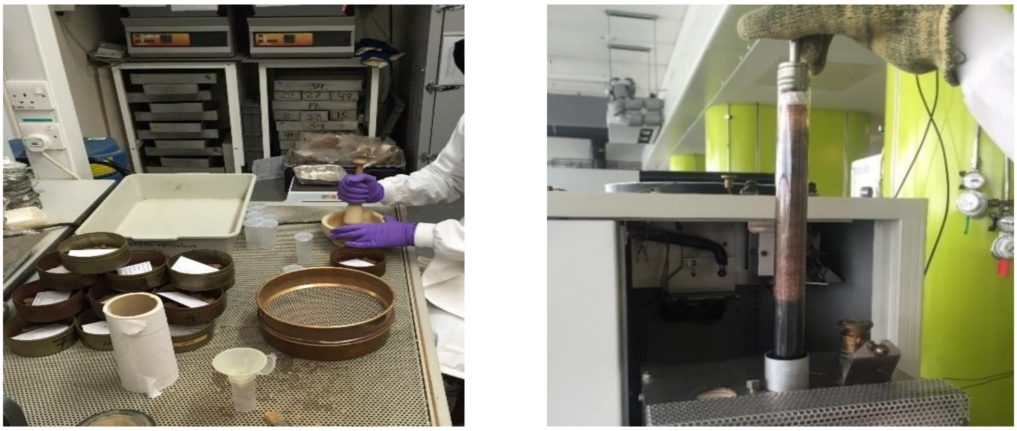


Figure 3.24. Soil preparation for total organic carbon (left), residues at the reduction tube in the elemental analyser (right)

The samples from the experimental field were air dried before grinding. Using a small pestle and mortar, the samples were broken down, with any large stones removed. The soil then was passed through a 2 mm mesh sieve (Figure 3.24). This was done so that the soil sample could be small enough to be finely milled (< 2 mm) in the next step into the mechanical grinder. After milling, the samples were dried for 24 hours to ensure that all moisture was removed.  The soil samples first had to be packaged for elementary analysis. 40-100 µg of the soil sample were weighed and placed into small silver-foil packaging. 2-3 drops of HCl (4mol/l) was added, until any reaction (bubbling/fizzing) stopped, this was left to sit for 30 minutes to fully react with the soil and burn any inorganic carbon left. The sample was then heated in a 90 °C for a minimum of 4 hours to ensure all of the moisture was removed, as the HCl used is very dilute. After drying, the silver-foil capsule was closed, and this package was tightly packed into a larger aluminium-foil capsule; ready to be analysed. The prepared packages of the soil samples were placed into the carousel through the automatic sample feeder, and the sample mass was entered into the software and aligned with the sample name and carousel number. The machine was free from carbon dioxide, with only oxygen for burning and helium as a carrier gas, which were the only gases present. This allowed the carbon to oxidise into carbon dioxide by heating to 900°C at a pressure of approximately 1.27 bar. The carbon dioxide released was measured by a thermal conductivity detector (TCD).

### 3.7.3 Microbial biomass carbon

The microbial carbon was assessed using the British Standard BS 7755: Section 4.4.2:1997 Determination of soil microbial mass-fumigation-extraction method which is identical to ISO 14240-2:1997. Sampling was carried out at the depth of 0-50 mm after tillage operation within all years every March and the results were expressed in μg C per 100 grams of soil. Soil (sediment) microbial biomass is the mass of intact microbial cells in a given sample. This is usually estimated from the measurement of the carbon or nitrogen contents of these cells. Through fumigation with chloroform for twenty-four hours, intact microbial cells will be lysed and the microbial matter released. Non-living organic matter is not seriously affected by such fumigation. The organic carbon extracted by 0.5 mol/l potassium sulphate is determined in fumigated and unfumigated samples, and the increase in extracted organic carbon is used to determine microbial biomass carbon. The next steps were followed for the fumigated samples: Field-moist soil (*sediment*) was weighted, containing a mass equivalent to 12.5g of oven-dry sample into a series of 200 ml glass bottles recording the masses to four decimal places. The mass of sample to take was calculated as follows (Eq. 3.4):

$$\text{Wet sample (g)} = \text{Dry mass required} \times (100 + WH_2O)/100 \qquad \text{Eq. (3.4)}$$

Where: dry mass is 12.5g and $W_{H_2O}$ is the percentage water content on an oven-dry basis. The desiccator used for the fumigation was lined with moist filter paper. The bottles were placed in the desiccator with a beaker containing approximately 25 ml ethanol-free chloroform and a few anti-bumping granules (Figure 3.25; left). Also a beaker was added containing approximately 25 ml of soda lime. The desiccator was evacuated until the chloroform has boiled vigorously for approximately 2 minutes. The vacuum tap on the desiccator was closed and left in the fume cupboard for 24 hours ±1 hour. After fumigation was completed, the beakers of chloroform were removed together with the filter papers. The chloroform vapour was also removed from the samples by repeated evacuation (6 times, two minutes each) of the desiccator. To extract organic carbon, 50ml ±2ml of 0.5 mol/l potassium sulphate solution were added by dispenser to each sample. They were placed on a side-to-side shaker (set at 300 min-$^1$) for 30 minutes ±1 minute. Each suspension is then filtered through a Whatman No. 42 (or equivalent) filter paper into separate sample bottles (Figure 3.25; right). These extracts were stored overnight in a refrigerator; longer storage could be achieved by storing the extracts at approximately -15 °C. For the non-fumigated samples the procedure was similar except the fumigation step.

Figure 3.25. Fumigation (left) and organic carbon extraction in separate plastic bottles (right)

Thus, after weighting the samples, 50ml ±2ml of 0.5 mol/l potassium sulphate was added, the samples were placed onto the side to side shaker for the same time and at the end the final step included again the carbon extraction with the Whatman filter (Figure 3.25; right).

### 3.7.4 Water stable aggregates

The water stable aggregates analysis was carried out for the depth of 0-100 mm using the wet sieving method. 80 bulk samples were collected within each experimental field after tillage operation for all years (every March). They were air dried, but before the soil was completely air dried, the large pieces were broken down into smaller pieces (Figure 3.26). The sample was then lightly ground using a small pestle and mortar, as it made it easier to pass the soil sample through the sieves. An air bench was used for this step as a health and safety measure, as it prevented minute soil particles being breathed in.

Figure 3.26. Soil preparation (left), samples prior to wet sieving (middle) and wet sieving (right)

Three steel meshed sieves (apertures of 10 mm 5 mm and 2.5 mm in descending order) were stacked on top of each other, with the 10 mm mesh sieve at the top and 2.5 mm sieve at the bottom. The sample was passed through the sieves thoroughly, and the material that was retained on the last sieve was collected for the analysis of water stable aggregates. The sample was then left to air dry again, as to create uniform moisture content; as air humidity can affect the stability of aggregates (Low, 1954).

To determine the water stable aggregates, 50 g of each sample were covered with 100ml of deionised water, left for 30 minutes to stand. Six sets of stacked sieves were prepared for the agitation; the soil was then placed on the top of each set of nested sieves Figure

3.26; middle). The sieves used, had apertures of 2 mm at the top, then 1 mm, 0.5 mm, 0.250 mm, and 0.106 mm at the bottom. At an angle, the sieves were lowered into the bath holes in the tub; this was done so that to prevent the sieves becoming trapped with air, preventing the soil to gradually move down through the sieves. The six set of sieves were then agitated for 17 minutes, whilst the water level in the tub was kept at a constant (Figure 3.26; right).

Immediately after the 17 minutes, all of the sieves were lifted from the water, and the material of > 0.5mm diameter which remained on the first three sieves (2mm, 1mm and 0.5mm sieve) were transferred to oven drying tins. The retained material > 0.5mm was then oven dried for a minimum of 24 hours at 105 °C and then weighed. After oven drying and by puddling, the retained material was then passed through the 0.5 mm sieve again, which washed away all of the soil so that to collect all the stones. The stones were oven dried again with the same temperature and duration, so that to calculate their weight.

### 3.7.5 Available nitrogen

The analysis was carried out based on the Rice et al. (2012) [Automated Hydrazine Reduction Method', p 4-90, Standard Methods for the Examination of Water and Wastewater, 22nd Edition, 2012] for the determination of ammonium-N and Nitrate-N extracted by potassium chloride. Sampling was carried out in March within all years after tillage operation to the depth of 0-50 mm at the same sampling points (Figure 3.21).

The fresh, field-moist soil sample was sieved through a 5.6 mm sieve, taking care to avoid smearing and compaction. 20 g ± 0.05 g of the <5.6mm fresh, field-moist sample were transferred into a 125 ml wide mouth plastic bottle. A small sample was taken in order to determine the dry matter and water content on a dry-mass basis ($W_{H_2O}$).

100ml of 2 mol/l potassium chloride solution were added, by measuring cylinder to each bottle. They were then placed on a side-to-side shaker (set at 300 $min^{-1}$) for 2 hours ±

10 minutes. For the extractions, the samples were filtered through a Whatman No. 4 (or equivalent) filter paper (Figure 3.27) and retained (refrigerated) for the determination of ammonium-N and nitrate-N.

Figure 3.27. Available nitrogen extraction

### 3.7.6 Earthworms population

Earthworms' population per unit area was a very demanding property to measure at the field and were counted on the same sampling points per plot (Figure 3.21), following the BS EN ISO 23611-1:2011 (Soil quality - Sampling of soil Invertebrates) and the OPAL (Open Air Laboratories) system. The pit dug had dimensions of 20 x 20 x 10 cm long, wide and deep respectively. This volume of soil was taken out and was laid on a plastic sheet so that the number of individuals per unit area can be thoroughly counted. A mustard liquid was prepared in order to be poured into the pit and irritate any deeper dwelling individuals, so that they would emerge from their burrows for collection. The mustard liquid was prepared as follows: for each sample pit identified, 30 g of mustard powder was placed into containers in the lab and 250 ml of water added. It was allowed to hydrate overnight at room temperature. In the field, a further 0.75 liters of water was added and shaken to ensure an even suspension (total volume 1 liter). The mustard was poured into the pit and the earthworms were collected 15 minutes after the solution has soaked away (Figure 3.28). The counted individuals were separated to juveniles and adults, whose length and weight was measured with a field ruler and balance respectively. Adults could be recognized by a well-distinguished saddle.

Figure 3.28. Mustard liquid production (left) and deep earthworms counting (right)

### 3.7.7 Soil hydraulic conductivity

The hydraulic conductivity was only measured in the second cropping season (2014-15) due to time limitations. It was measured using the Mini Disk Infiltrometer (Decagon Devices, Inc) which, as its name indicates, was a cylinder with a perforated disk shape base. The water needed for operation could easily be carried in a personal water bottle and it was measuring water infiltration in terms of unsaturated soil hydraulic conductivity. The infiltrometer had two chambers. The upper and lower chambers were both filled with water. The top chamber (or bubble chamber) controlled the suction. The lower chamber contained a volume of water that infiltrated into the soil at a rate determined by the suction selected in the bubble chamber. As mentioned in the user manual (Decagon Devices, 2017) in sandy soils where infiltration occurs very quickly, a suction of 6 cm may be helpful, and a suction rate of 0.5 cm for more compact soil with slower infiltration. In the present study because of the clay and clay loam texture and as there was no soil compaction issue, a suction of 3.5 cm was chosen. The lower chamber was labeled like a graduated cylinder with volume shown in ml. The bottom of the infiltrometer had a porous sintered stainless steel disk which did not allow water to leak in open air.

Once the infiltrometer was placed onto a soil, water begun to leave the lower chamber and infiltrate into the soil at a rate determined by the hydraulic properties of the soil (Figure 3.29). As the water level dropped, the volume was recorded at specific time intervals (every 5 minutes for the clay and clay loam soils of the study area).

Figure 3.29. Unsaturated hydraulic conductivity measurements with the mini disk infiltrometer

Worth mentioning that in case the soil surface was not level enough for the disk to stand, a thin layer of pure silica sand was placed underneath so that to achieve good disk - soil contact (Figure 3.29).

## 3.8 Crop growth and yield

Crop performance per treatment was first determined in terms of the mean annual yield per hectare. However to understand the basis for potential yield differences, additional measurements were carried out to determine the harvest index, plant density, blackgrass infested areas, straw residue retained on the surface, NDVI and soil available nitrogen as described (Table 3.8).

### 3.8.1 Residue cover

Surface residue was assessed once, prior to the start of the cropping season for both fields and straight after drilling took place. Residue was measured using a 1 m$^2$ quadrat with 0.1x0.1 m internodes. The quadrat was placed on the same sampling points as the rest of the properties within each plot and measurements included how many of the internodes felled over the surface crop residues and not over bare soil (Figure 3.30).

Figure 3.30. Surface residue measurements with a 1 m$^2$ quadrat

The numbers of the internodes that do not fall onto bare soil, include the surface residue percentage (x out of 100 internodes fall onto residue). The outcome, which is analysed in detail in chapter 3, showed a highly significant difference, between treatments straight after the drilling.

### 3.8.2 Annual yield

Yield in all three cropping seasons was measured in both fields using a New Holland CX 8080 combine harvester. The combine harvester had a 9 m wide cutter-bar which allowed a clear cut down the centre of the 12 m width of each experimental plot. The measuring system-software on CX harvesters is a high accuracy yield sensor developed by New Holland (New Holland Ltd, 2016). The sensor plate, between grain elevator and grain tank filling auger, is fitted to a pivoting device with a counterweight. This minimises the friction of the grain and provides mass measuring whatever the kernel size or shape, the grain density and the moisture or impurity content (New Holland Ltd, 2016). The yield results (expressed in t ha$^{-1}$) were obtained from the combine's harvester measuring system and the output were points (called for simplicity yield points) depicting the combine harvester's track. These points corresponded to the weight of the batch of grain at the particular instant and place and range from red to green indicating low or high yields. In Figure 3.31 for instance, yields in green (4.98-6.95 t ha$^{-1}$) symbolize high values, yields in orange-yellow medium values (2.20-4.98 t ha$^{-1}$) and low yield values in red color (0.28-2.20 t ha$^{-1}$).

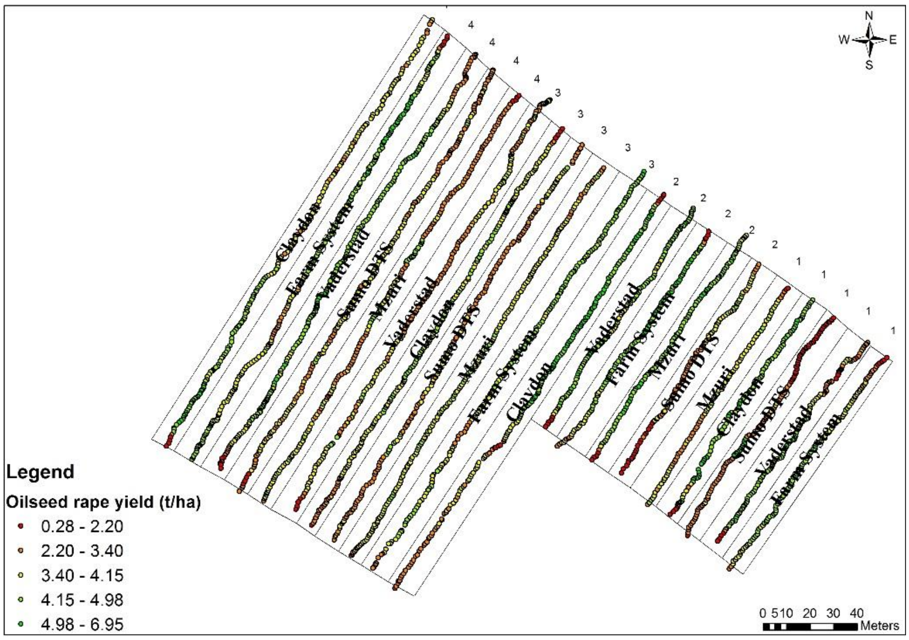


Figure 3.31. Example of yield data obtained for each plot in Snagsborough for oilseed rape in 2016

### 3.8.3 Harvest Index

The harvest index is the dry mass of the economic component of the crop (i.e. the grain) expressed as a proportion of the above-ground dry mass. Because of time limitations, this was monitored in order only to get a feel of its value per crop and the results were not statistically examined. 10 plants of each crop were collected (where accessible) across both fields at harvest time. The procedure was as followed: Initially the combine's cut height was recorded so that to be known the height of stubble in the field. The plants were collected and brought into the laboratory, they were weighted and oven dried at 80$^{o}$C for 30 hours (personal communication with Richard Andrews) and then weighted again. The outcome was the calculation of the above ground dry matter which was assessed as an average from the 10 plants. Once both the nominator and denominator were available then it could be calculated the Harvest Index from the following Equation 3.5:

$$\text{Harvest Index} = \frac{\text{Grain yield (dry matter basis)}}{\text{Above ground dry matter}} \qquad \text{Eq. (3.5)}$$

### 3.8.4 Oilseed rape oil content

The oil content of the oilseeds was also determined after crop's harvest following the detailed hexane extract method (British ISO 659:2009). Similarly as the Harvest Index, the extraction was carried out in one representative replicate (5 plots), usually collected from the middle of the plot, for all treatments. That's because of limited resources with regards to time and money available to carry out 80 oil content measurements per field.

A synopsis of steps of the method is as follows: i) the moisture content of the seed was calculated prior to extraction of the oil, ii) the seeds were ground, iii) 10 ± 0.5 g of ground test seeds was weighted, iv) within 30 mins of grinding the seeds were transfered into the thimble (wool plug the thimble), v) the necessary quantity of solvent (hexane) was poured into the flask vi) the flask was fitted to the extraction apparatus on the electric heating bath, vii) heating was carried out so that the rate of reflux was 3 drops per second, viii) after cool down, the solvent was removed from the flask by distillation and the flask was allowed to cool in a desiccator for 1 h and weigh to the nearest 1 mg (Figure 3.32).

Figure 3.32. Ground seeds (left) and oil extraction with hexane solvent (right)

### 3.8.5 Plant density

The plants density measurements (number of plants per unit area) were carried out within each single experimental plot for both fields and were recorded alongside with their development stages. The results were expressed in number of plants per meter square.

Figure 3.33. Plant density counting at the field site

The sampling points were the same as with bulk density (Figure 3.21) and were also repeated at least once within the cropping season. The measurements were carried out using a known size (1 m$^2$) wire (Figure 3.33). When a certain measurement of plant count ended, their development stages were identified using a reference guide for wheat and oilseed (Farman et al. 1989; AHDB Cereals & Oilseeds 2015).

### 3.8.6 Blackgrass

Regarding blackgrass infestation, the first step was to record the spatial distribution of blackgrass on the infested fields. It is worth mentioning that the weed issue appeared when the wheat was planted in the heavy soil field (Top Furze) and mostly in areas where there was poor infiltration and much water ponding. When the wheat was in grain development stage (around June 2014 and 2016), the blackgrass infested areas were easily distinguished by human eye and their spatial distribution was recorded, as polygons, using a Trimble Geox 6000 GPS.

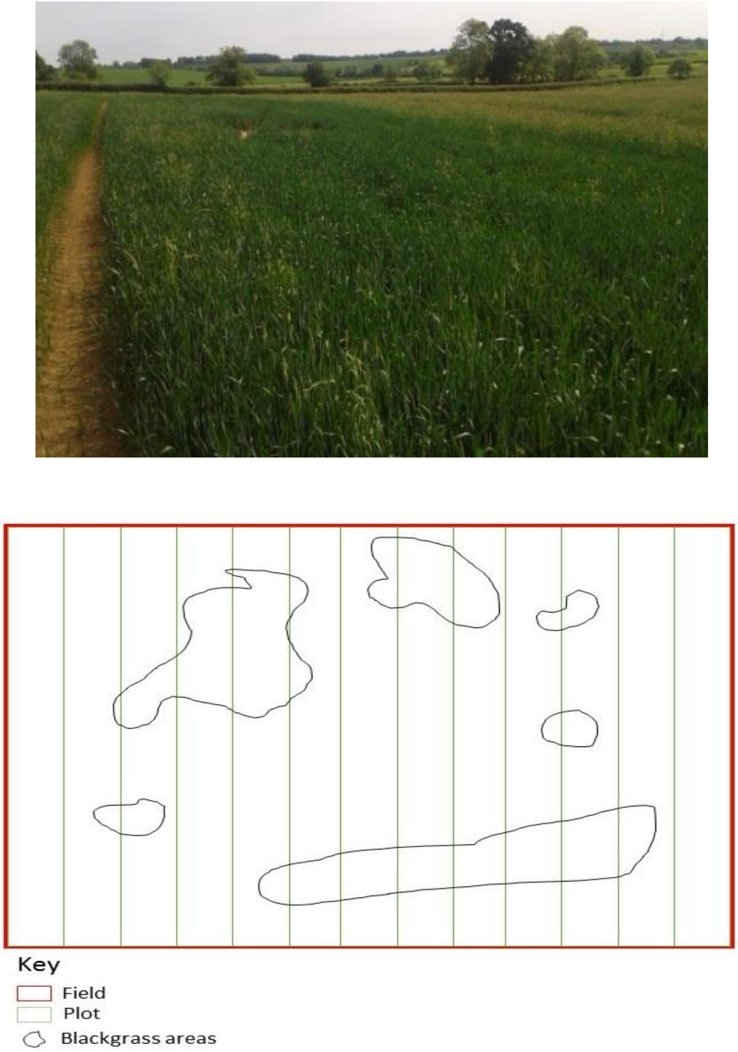


Figure 3.34. Blackgrass areas in Top Furze in 2015-16 (top) and a random non-scaled example of how the infested areas were digitized (bottom)

The procedure followed the next steps (Figure 3.34): i) eye-distinguish a blackgrass infested area, ii) start at one end to create a polygon shapefile with the GPS unit and walk along the border between blackgrass and clear areas, iii) close the polygon at the same place (start/end). Blackgrass plants and heads counts were also measured to get a clearer picture of its distribution and density.

### 3.8.7 Normalised Difference Vegetation Index (NDVI)

Normalised Difference Vegetation Index measurements were carried out during the cropping season using the The Crop Circle ACS-470 active crop canopy sensor (Holland scientific, Inc) whilst avoiding scanning close to the plots' borders and avoiding visible traffic lanes as well. The equipment was mounted on an atv quad bike (Figure 3.35).

Figure 3.35. Scanning oilseed rape for NDVI in Snagsborough in 9th of December 2015

At the end of scanning a csv file was produced with the coordinates and the measurements at the specific time and place. This file was then inserted into the ArcMap software to create a shapefile of NDVI as shown by the equation 3.6 where VIS and NIR stand for the spectral reflectance measurements acquired in the visible (red) and near-infrared regions, respectively.

$$\mathrm{NDVI} = \frac{\mathrm{NIR-VIS}}{\mathrm{NIR+VIS}} \qquad \text{Eq. (3.6)}$$

Earthworms numbers were not measured in the first cropping season (2013-14) within the oilseed rape field (Snagsborough) and total organic carbon was also not measured for the second depth (150-200 mm) in the last cropping season (2015-16) in Snagsborough.

## 3.9 Economic profitability

The methodology used for the economic analysis, carried out as a cost-benefit analysis, alongside its results will be presented as a separate section in chapter 7.

# 4 CHARACTERISATION OF SOIL TILLAGE TREATMENTS

The previous chapter describes the field experiment at Lamport Hall Estate in Northamptonshire. This chapter describes a more detailed examination of some of the tillage equipment using the soil bin facilities at Cranfield University. The **objectives** of the soil bin experiment, reported here, are to a) measure the force requirements of five tillage implements under controlled conditions, b) measure and evaluate soil disturbance and c) estimate the analogous fuel consumption.

## 4.1 Introduction

The following parameters can be measured in the soil bin: i) horizontal, vertical and moment forces, ii) area and volume of above and below ground soil disturbance, iii) assessment of soil failure, and iv) fuel consumption estimation (based on the horizontal force requirements).

The horizontal draught force is the force acting upon an implement in a horizontal direction required to pull it through the soil. The vertical force is the force acting in a vertical direction on the implement which can assist or prevent penetration into the soil. It is positive when acting upwards and negative when acting downwards. Thus good soil penetration is indicated by the negative sign, meaning that the implement is pushed into the soil greater than an implement which has a positive vertical force. The turning effect of the force, or the moment, is the product of a force and its distance from an axis which causes rotation about that axis (Godwin, 1975).

Different tillage implements will result in different levels of soil disturbance which can be described in terms of the depth, width, area and volume. From measurements of below ground disturbance, it is also possible to obtain information about soil failure, the shape, area and volume of disturbed soil, specific resistance, and the implement performance (Godwin and Spoor 1984). Bligh (1989) reported that drilling seeds with minimal soil disturbance, e.g. only disturbing a narrow width in the drilling row, can reduce soil erodibility (susceptibility to erosion). Rab et al. (2005) also reports that reduced soil disturbance can help minimize the local decline of species that regenerate from underground habitats.

The soil bin facilities also allow assessment of soil failure. Based on the literature there is a “critical depth“, above which specific tillage implements can operate optimally (Ndisya 2016; Godwin & Spoor 1977; Manuwa 2009; Conte et al. 2011). Spoor and Godwin (1978) have shown that the soil at depth can fail in one of two ways: (i) forward and upward in a brittle manner, with well-defined failure planes, termed crescent failure, or (ii) locally with a compressive type of failure. The brittle failure causes soil loosening, whereas the compressive failure causes soil compaction in a compressible soil. The type of failure depends upon the resistance to deformation in each case. For effective soil loosening crescent failure should occur and therefore the position of the critical depth influences the maximum useful working depth of a tine (Manuwa, 2009).

Thus critical depth is simply the depth below which the amount of soil loosening generated by the tine is minimal and the lateral extent of the major soil failure planes to the side of the tine changes little with increasing depth (Spoor and Fry 1983). The actual critical depth (Figure 4.1) is dependent upon the implement’s geometry, working depth to width ratio (aspect ratio), and soil conditions (Spoor and Fry 1983).

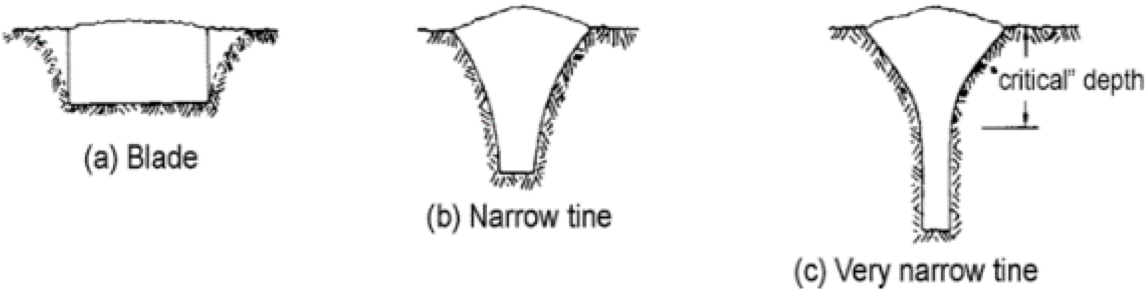


Figure 4.1. Effect of implement depth/width ratio on patterns of soil failure, after Godwin (2007).

Godwin & Spoor (1977) indicated that as the aspect ratio increases the soil failure changes to that shown in Figure 4.1(c), where there is a small crescent close to the soil surface but the soil at depth is forced laterally to produce a slot. They also pointed out that a tine is working below its critical depth when its aspect ratio is approximately 6.0.

The draught required during tillage is a function of soil properties, working depth, implement geometry, travel speed, and the width of the implement (Chandon and Kushwaha 2002). Hence estimates of implement performance should be reported in the context of soil conditions. For example Chandon and Kushwaha (2002) highlight that soil properties such as moisture content, bulk density, cone penetrometer index, and soil texture determine the energy required to carry out tillage. In turn the energy required per unit time can be related to fuel consumption per unit time (Grisso et al. 2014; Ishak, Ismaif and Burkhardt, 1993). Mileusnić et al. (2010) report that the most energy demanding part of crop production is often tillage. Compared to conventional tillage systems, fuel consumption can be significantly reduced with conservation tillage systems (Moitzi et al. 2014). The intensity of tillage depends on the number of tillage operations, power transmission (active by PTO or passive by drawbar power), implement geometry, and depth of operation (Godwin and O’Dogherty 2007). According to Mileusnić et al. (2010), tillage depth directly influences fuel consumption. In the same study, it was added that conservation tillage is characterized by the reduction of the required operations that decrease the tractor’s working time and load, thus minimizing the fuel consumption and reducing associated production costs.

As indicated at the start of this Chapter, the **objectives** of the soil bin experiment, reported here, are to a) measure the force requirements of five different tillage implements under uniform soil conditions, b) measure and evaluate soil disturbance and c) estimate the analogous fuel consumption.

## 4.2 Methodology

### 4.2.1 Description of the soil bin facility

The soil bin and processor at Cranfield University is a 20 m long, 1.7 m wide and 0.75 m deep soil dynamics facility which can be prepared in 50 mm layers to create a number of highly controlled and repeatable test profile conditions, with bulk densities indicative of field conditions with moisture contents up to 20%. This allows the creation of customised soil profiles. The soil bin processor has instrumented mounting points on an extended octagonal ring transducer for the testing of tillage implements, tyres and sensors. The variable drive system allows testing at both low and high speeds. The facility can also be used to determine draught and vertical force requirements and tillage efficiency. The processor runs on tracks on either side of the bin (Figure 4.2).

Figure 4.2. Cranfield University's soil bin facility

### 4.2.2 Tillage equipment testing

Ideally the selection of the tillage implement to be tested would fully match the five treatments tested in the field experiment. However the number of pieces of equipment tested was constrained by time and the agreement of the equipment manufacturers to provide implements. The five pieces of equipment that were tested comprised parts of: a) the Väderstad Seed Hawk SH 800, b) the Väderstad Rapid A 400 S, c) the Mzuri Pro Til 3, d) the Claydon Hybrid drill, and e) the Sumo Trio (Table 4.1; Figure 4.3). For the

Väderstad Seed Hawk all of the parts that comprise a drilling row were received. By contrast for the Väderstad Rapid only the working disc with an attached coulter was tested. For the Claydon Hybrid, only the working and the seeding tine (coulter) were tested and for the Mzuri Pro Til 3 and Sumo Trio, only the working tines were tested. These combinations allow comparisons between different type of working tines or seeding tines. It would not be a fair test to compare a working tine to a whole row of implements and its components and vice versa. For simplicity and consistency, this chapter will only present the results for the main working component. The additional diagrams and results from the split tests of Väderstad Seed Hawk and Claydon (Table 4.1) are presented in Appendix B.

Table 4.1. Received implements from each manufacturer and how they were tested

| Manufacturer | Implements received | Split test into |
|---|---|---|
| Väderstad Seed Hawk | Whole unit | Whole unit, fertiliser coulter, drill coulter, wheel |
| Väderstad Rapid | Working disc | - |
| Claydon Hybrid | Working and seeding tine | Working tine, seeding tine |
| Mzuri Pro Til | Working tine | - |
| Sumo Trio | Working tine | - |

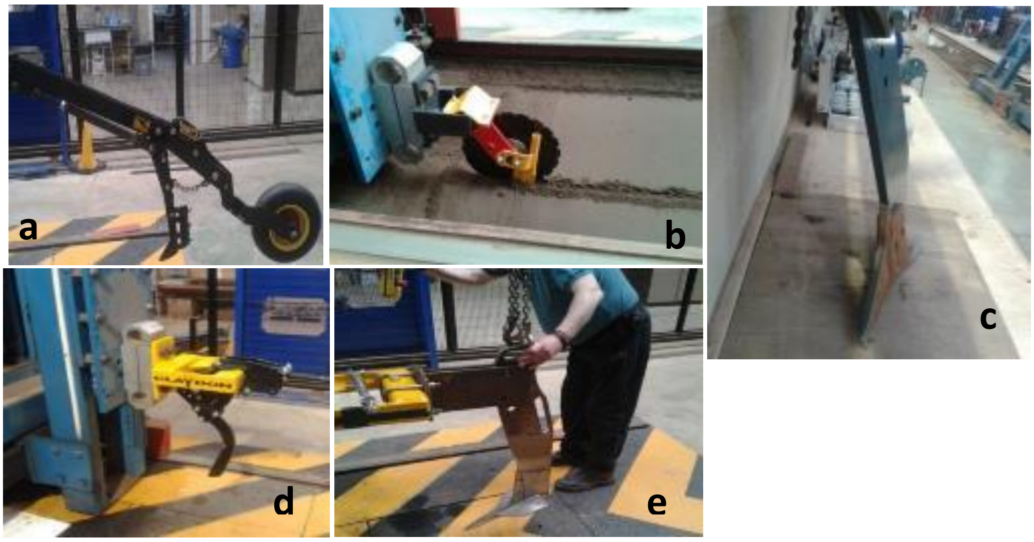


Figure 4.3. Tillage implements that were delivered and tested in the soil bin from a) Väderstad Seed Hawk, b) Väderstad Rapid c) Mzuri Pro Til, d) Claydon Hybrid and e) Sumo Trio

All the tests were carried out at the speed of 6 km h$^{-1}$ (1.7 m s$^{-1}$). Ahaneku and Ogunjirin (2005) also supported that a forward speed of 6.8 km h$^{-1}$ resulted in appreciable amelioration of soil structure as reflected in improvements in the soil strength properties which generally decreased with increasing speed but increased with depth of tillage. Analysis of the soil's texture in the bin showed it to be sandy loam. Ideally, the soil in the bin should be in a uniform condition in terms of its bulk density before the start of the experiment, but there appears to be a systematic bias in the processing equipment which prevents this. The Senior Technician in charge of the processor, Roy Newland, explained that the soil in the bin had a consistent density gradient ranging from less dense on the left hand side to more dense on the right hand side. This non-uniformed density will result in different outcomes for example in terms of applied forces and soil disturbance. Hence it was decided (Personal communication with Dick Godwin) to present the results for both parts of the bin in terms of "light (left)" and "right (dense)" parts. Due to the replications of measurements, results for both locations are presented.

### 4.2.3 Calibration of transducer

Before commencing with the analysis of the different implements, the octagonal ring transducer was calibrated to ensure accuracy. The Cranfield extended octagonal ring transducer consists of a machined block, normally of steel or aluminum (Godwin, 1975). Strain gauges are connected to resistors which measure voltage. The transducer was calibrated so that a known applied weight should give the same output in kN every time. Figure 4.4 shows the application of the weights and their corresponding values in volts.

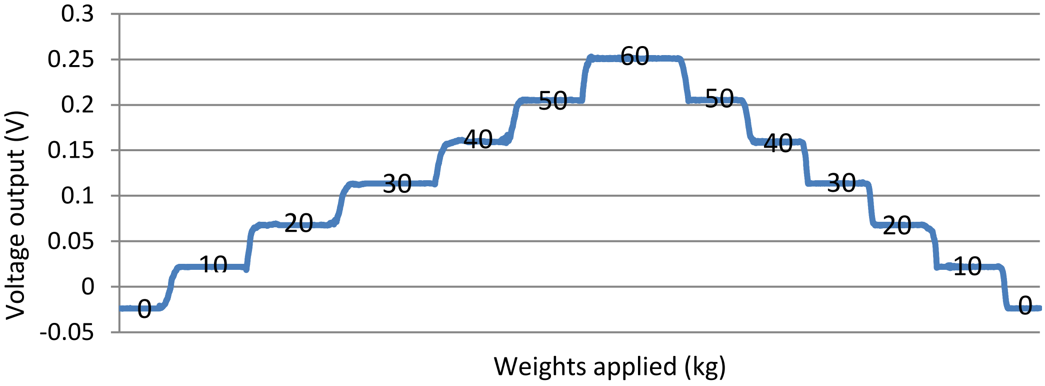


Figure 4.4. Calibration of the soil bin's octagonal ring transducer

Once the voltage outcome for certain kilos is known (Table 4.2) then the calibration curve can be derived. The derived relationship had a correlation coefficient ($r^2$) of 1 (Figure 4.5).

Table 4.2. Actual voltage values and their relationship with the kN

| Mass applied (kg) | Mean voltage (V) | Energy (kNm) | Force (kN) |
|---|---|---|---|
| 0 | -0.02380 | 0 | 0 |
| 10 | 0.02160 | 0.098067 | 0.754358 |
| 20 | 0.06770 | 0.196133 | 1.508715 |
| 30 | 0.11315 | 0.2942 | 2.263073 |
| 40 | 0.15916 | 0.392266 | 3.017431 |
| 50 | 0.20450 | 0.490333 | 3.771788 |
| 60 | 0.25089 | 0.588399 | 4.526146 |

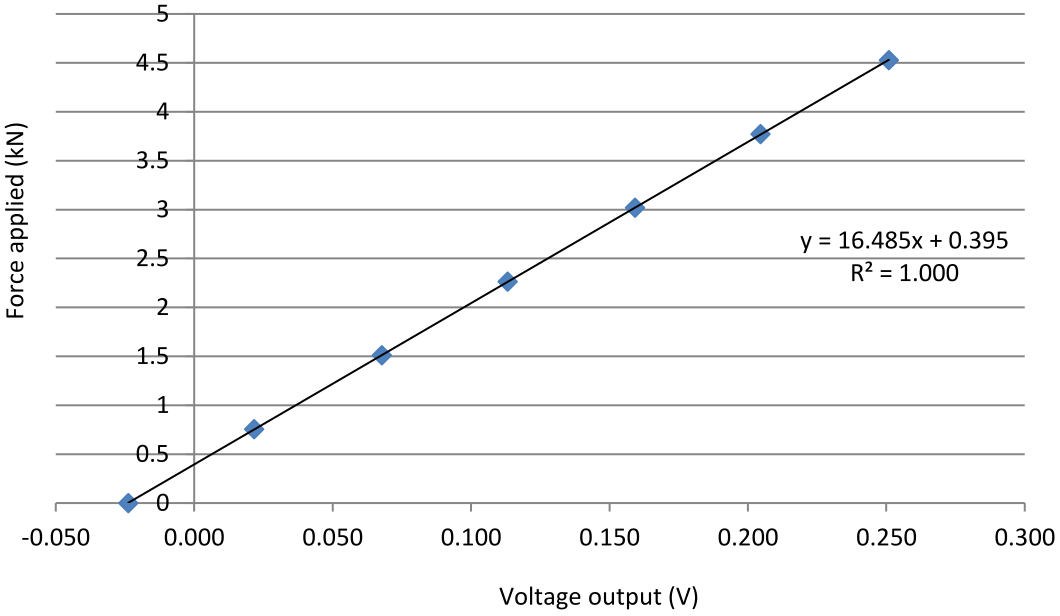


Figure 4.5. Linear correlation between the voltage output and the corresponding vertical force value in kN

### 4.2.4 Measurements taken

In order to measure the draught requirements of five different tillage implements under uniform soil conditions and their effect on soil disturbance, a range of properties were measured (Table 4.3).

Table 4.3. Measurements taken in the soil bin experiment

| Before tillage runs | During tillage runs | After tillage runs |
|---|---|---|
| Bulk density (Mg $m^{-3}$) | Horizontal draught (kN) | Bulk density (Mg $m^{-3}$) |
| Penetration resistance (MPa) | Vertical force (kN) | Penetration resistance (MPa) |
| | Moment (kN) | Fuel requirements (l $s^{-1}$) |
| | | Above ground disturbance ($m^2$) |
| | | Below ground disturbance ($m^2$) |

The octahedral ring mounted on the soil bin processor was used to measure three forces simultaneously: the horizontal (draught) force, the vertical force and the moment. The octahedral ring was connected to electrodes in a three channel assembly (0, 1, and 2). Each channel corresponded to a single force (0 = draught, 1 = vertical, 2 = moment). All the forces were initially measured in volts (V) originated from the electrodes, which were connected to the ring, and they were finally automatically transformed and displayed, after calibration, into kilonewtons (kN). It was important for the tillage implements to be fitted properly to the octahedral ring before they were pulled by the processor through the soil. After the end of a single run, a Microsoft Excel file was generated by the soil's bin software (Daisy Lab) including all three applied forces at the particular time and point of the bin. Finally the associated diagram was produced which contained the values of each force at each measurement at a particular point and time. Above-ground soil disturbance was measured with the laser scan device at 6 m intervals along the length (12 m) of the tillage line. A Micro-Epsilon laser sensor was mounted onto a horizontal metal bar which fitted directly above the soil surface. The sensor was drawn across the horizontal bar at a steady rate and the laser scanned the vertical distance between the bar (as the reference point) and the soil surface. Any vertical displacement (+ or -) in the soil surface at that point was recorded using the accompanying DaisyLab software. The scanner has a vertical resolution of 6 microns, which was a greater resolution than was necessary for these tests. The laser scans were carried out at three places across the length of the upper middle and bottom part. Above ground disturbance corresponded to the extent of the surface soil that was disturbed due to the influence of the tillage implement and below ground disturbance referred to the disturbance of the soil profile that was created by an implement down to its working depth. Following the methodology of the associated field work (section 3.6.1), bulk density sampling and penetration resistance readings were carried out before and after each experimental run, to simulate as closely as possible the field work protocols in terms of the soil compaction properties. The bulk density rings were 50 mm in height and 50 mm in diameter. Soil moisture content was also monitored from the bulk density rings. Penetrometer readings were carried out either between 0 and 100 mm or between 0 and 200 mm for implements that operated below 100 mm. In order to pick up any influence of the tested implements on bulk density and penetration resistance, nine bulk density samples (three from the front, three from the middle, and three from the back sections of the bin) were collected before the start and after the end of each experimental run.

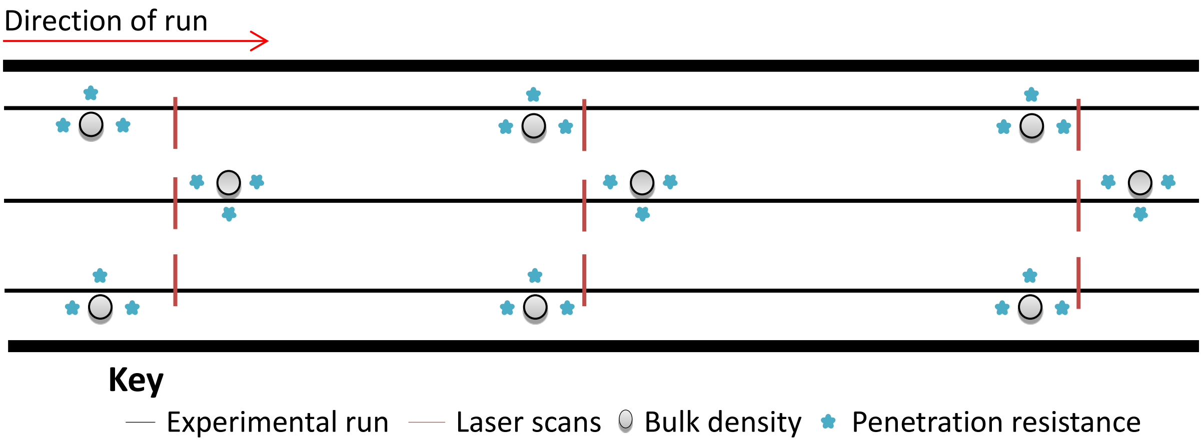


Figure 4.6. Schematic illustration of the layout of the soil bin measurements

After each run, the second set of bulk density samples was collected as closely as possible to the run line. Finally both before and after the experimental runs, three penetration resistance readings were taken in the vicinity of each bulk density ring. The experimental runs, the bulk density samples, penetration resistance readings (before and after the runs) and the laser scans were replicated three times for each of the five types of tillage implements. The laser scans recorded the detail 2-D micro relief of the soil crossed by the laser beam. This was used to calculate a volume of soil disturbance by assuming a 1 m distance of travel. The fuel requirement needed to pull the implements through the soil was estimated using Equation 4.1 (Inns and Kilgour 1978; Serrano et al. 2007). Several assumptions were used in the calculation; a slip efficiency of 0.9, a transmission efficiency of 0.8, a thermal input factor of 3 (personal communication with R. Godwin, 2015) and the specific energy of diesel 38.6 x $10^6$ J $l^{-1}$ (Demirel, 2012).

$$\text{Fuel requirement (l s}^{-1}\text{)} = (((F \times S / \eta_s) / \eta_t) \times T_h) / Se \qquad \text{Eq. (4.1)}$$

Where $F$ = draught force (N), $S$ = speed (m $s^{-1}$), $\eta_s$ = slip efficiency, $\eta_t$ = transmission efficiency, $T_h$ = Thermal input power factor, $Se$ = specific energy of diesel (J $l^{-1}$).

## 4.3 Results

The measurements were carried out separately for each implement of the unit and the results present in this section, concern the main working tine or disc. The remaining individual components are presented in Appendix B. Soil moisture for all runs was not significantly different and ranged between 7.0-9.5%.

### 4.3.1 Väderstad Seed Hawk

The Seed Hawk uses the fertilizer tine as the main working tine regardless of whether fertilizer is applied or not. The fertilizer tine depth was adjusted (by sliding a metal pin into a groove) to the 25 mm used in the field. It has a width of 13.5 mm and rake angle of 50° (Table 4.4; Figure 4.7).Väderstad Seed Hawk main working tine; left: in the soil bin experiments; right: computer-aided design (CAD) showing its geometry.

Table 4.4. Väderstad Seed Hawk fertiliser tine working depth and geometry

| | Working depth (mm) | Width (mm) | Rake angle in degrees (°) |
|---|---|---|---|
| Fertiliser tine | 25 | 13.5 | 50 |

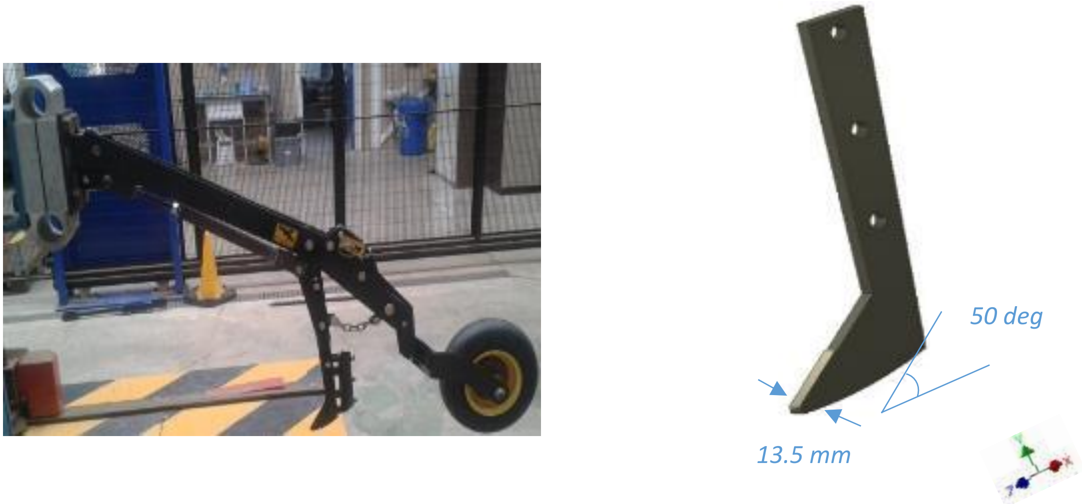


Figure 4.7. Väderstad Seed Hawk main working tine; left: in the soil bin experiments; right: computer-aided design (CAD) showing its geometry

Each set of measurements consisted of three separate runs across the width of the soil bin. Because of the very shallow working depth of the Seed Hawk (25 mm), three runs across the width of the bin could be carried out at the same time. The mean bulk densities (0-50 mm) and penetration readings (0-100 mm) (Table 4.5) showed systematic differences between the left and the right parts of the bin. As mentioned in Section 4.1, soil can fail (i) forward and upward in a brittle manner (crescent failure) resulting in soil loosening or (ii) locally with a compressive type of failure causing soil compaction. In each case, the Seed Hawk caused no significant increase in soil bulk density, suggesting crescent failure and that the implement was working above its critical depth.

Table 4.5. Seed Hawk: mean values for bulk density, penetration resistance and force requirements for both left and right parts of the bin before and after the runs

| | *Left part* | | *Right part* | |
|---|---|---|---|---|
| | Before run | After run | Before run | After run |
| Bulk density (Mg m$^{-3}$) | 1.51 a | 1.55 a | 1.61 a | 1.63 a |
| Penetration (MPa) | 0.94 b | 0.81 b | 1.56 a | 1.26 ab |
| Horizontal draught (kN) | 0.19 a | | 0.21 a | |
| Vertical force (kN) | 0.76 a | | 0.80 ab | |

*Means with the same letter are not significantly different ($p>0.05$) and apply to rows

There was a tendency for the bulk density to be greater in the right part of the soil bin, and the measured horizontal draft in the right part (0.21 kN) was higher than in the left (0.19 kN) (Table 4.5). The vertical forces for the left (0.80 kN) and the right part (0.76 kN) were greater than the horizontal force. As discussed in the methodology, above-ground disturbance scans were carried out at surface level after the experimental runs. Below-ground disturbance scans were also taken after excavating, by hand, the soil until the working depth was easily identified by hand (Figure 4.8).

Figure 4.8. Laser scans for the Väderstad Seed Hawk treatment

The above ground disturbance (blue line in Figure 4.9) indicates the disturbance caused by the fertilizer tine on its own and the ‘after wheel disturbance’ (green line) indicates the amount of soil disturbance following the wheel’s passage. The below ground disturbance was 0.0015 m$^2$ and the width of disturbance was 83 mm. The above-ground disturbed soil (blue line) occupied an area of 0.0027 m$^2$. The disturbance after the passage of the wheel (green line) was 0.0018 m$^2$.

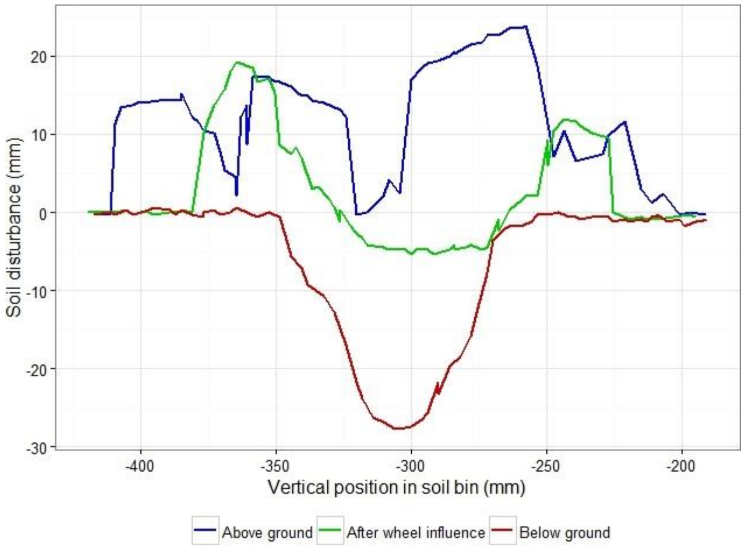


Figure 4.9. Above ground, below ground and after the influence of the wheel disturbance by the Väderstad Seed Hawk fertilizer tine

This efficiency of the system can be described by the specific draught or specific resistance (Spoor and Godwin, 1978) in kN m$^{-2}$ i.e. the draught force per cross-sectional area of tilled soil. The specific resistance for the fertilizer tine of the Seed Hawk was 126.6 kN m$^{-2}$ and 140.0 kN m$^{-2}$ for the light and dense part of the soil bin respectively (Table 4.6).

Table 4.6. Summary table of the soil bin results for the Väderstad Seed Hawk

| Part | Working depth (mm) | Width of disturbance (mm) | Area of soil disturbed (m$^2$) | Horizontal force (kN) | Vertical force (kN) | Specific resistance (kN m$^{-2}$) |
|---|---|---|---|---|---|---|
| Light (left) | 25 | 83 | 0.0015 | 0.19 | 0.56 | 126.6 |
| Dense (right) | 25 | 83 | 0.0015 | 0.21 | 0.65 | 140.0 |

### 4.3.2 Väderstad Rapid

Only the working disc and coulter of the Väderstad Rapid were used in the soil bin tests. The working depth of the disc (diameter of 410 mm) is 25 mm (Table 4.7; Figure 4.10). Surface bulk density sampling was carried out at 0-50 mm and penetrometer readings at 0-100 mm depth.

Table 4.7. Väderstad Rapid disc working depth and diameter

| | Working depth (mm) | Diameter (mm) |
|---|---|---|
| Main disc | 25 | 410 |

Figure 4.10. Väderstad Rapid's working disc left: in the soil bin experiments; right: computer-aided design (CAD) showing its geometry

The use of the Rapid disc had no significant effect on the measured bulk density or penetration resistance (Table 4.8). The mean horizontal draught was 0.08 kN and 0.12 kN on the left and right of the soil bin respectively, and the corresponding vertical force requirements were 0.88 and 1.35 kN. This is half the horizontal but twice the vertical force as the Seed Hawk.

Table 4.8. Väderstad Rapid: mean bulk density, penetration resistance and force requirements for both left and right parts of the bin before and after the runs

| | *Left part* | | *Right part* | |
|---|---|---|---|---|
| | Before run | After run | Before run | After run |
| Bulk density (Mg $m^{-3}$) | 1.44 a | 1.49 a | 1.60 a | 1.54 a |
| Penetration (MPa) | 1.25 a | 1.14 a | 1.38 a | 1.16 a |
| Horizontal draught (kN) | 0.08 a | | 0.12 a | |
| Vertical (kN) | 0.88 ab | | 1.35 a | |

* Means with the same letter are not significantly different ($p>0.05$) and apply to rows

The above and below-ground disturbance caused by the Rapid (Figure 4.11) shows clearly where the coulter was working, namely the grooved right part of the below ground profile (red line). The width of disturbance was 87 mm, the area of the below ground disturbed soil was 0.0009 m$^2$, and the maximum height of above-ground disturbance was 13 mm. For each meter travelled, the Väderstad Rapid disc disturbed 0.0009 m$^3$ of soil. The above ground disturbed soil (blue line) was occupying an area of 0.0011 m$^2$ (Table 4.9). Its specific resistance was 133.3 and 88.8 kN m$^{-2}$ for the dense and light part respectively.

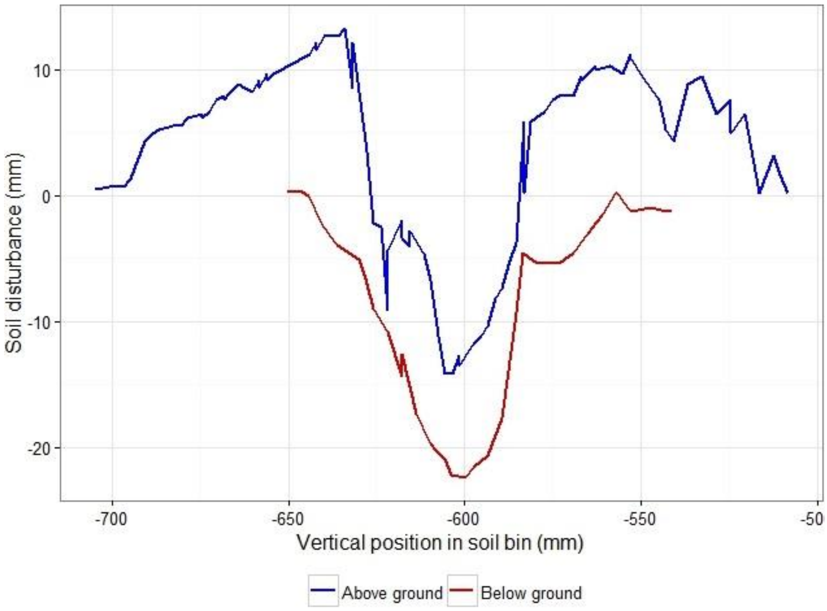


Figure 4.11. Above and below ground disturbance caused by the Väderstad Rapid disc and coulter

Table 4.9. Summary table of the soil bin results for the Väderstad Rapid

| Part | Working depth (mm) | Width of disturbance (mm) | Area of soil disturbed (m$^2$) | Horizontal force (kN) | Vertical force (kN) | Specific resistance (kN m$^{-2}$) |
|---|---|---|---|---|---|---|
| Light (left) | 25 | 87 | 0.0009 | 0.08 | 0.88 | 88.8 |
| Dense (right) | 25 | 87 | 0.0009 | 0.12 | 1.35 | 133.3 |

### 4.3.3 Claydon Hybrid

Claydon Ltd supplied a unit comprising the working tine and the seeding tine for the soil bin experimental runs. The working tine, which had a width of 20 mm, was used at a working depth of 150 mm (Figure 4.12; Table 4.10). This section describes solely the results for the working tine, but Appendix B includes the results of the whole unit and the seeding tine.

Table 4.10. Claydon tine working depth and geometry

| | Working depth (mm) | Width (mm) | Rake angle in degrees (°) |
|---|---|---|---|
| Tine | 150 | 20.0 | 70 |

Figure 4.12. Claydon main working tine received for the experimental runs left: in the soil bin experiments; right: computer-aided design (CAD) showing its geometry

Table 4.11. Claydon: mean bulk density and penetration resistance at 0-50 mm and 150-200 mm alongside force requirements for both parts of the soil bin before and after the runs

| | *Left part* | | *Right part* | |
|---|---|---|---|---|
| | Before run | After run | Before run | After run |
| Bulk density (Mg m$^{-3}$) (0-50 mm) | 1.54 b | 1.50 b | 1.60 a | 1.54 ab |
| Bulk density (Mg m$^{-3}$) (150-200 mm) | 1.52 a | 1.53 a | 1.57 a | 1.56 a |
| Penetration (MPa) (0-50 mm) | 1.46 ab | 1.43 ab | 1.51 a | 1.35 b |
| Penetration (MPa) (150-200 mm) | 1.35 c | 1.68 b | 2.10 a | 2.18 a |
| Horizontal force (kN) | 1.02 ab | | 1.62 a | |
| Vertical force (kN) | 0.35 ab | | 0.67 a | |

* Means with the same letter are not significantly different ($p>0.05$) and apply to rows

The leg's working depth was set similar to the field conditions, 150 mm, and bulk density was measured at the surface level (0-50 mm) and at the tine's working depth (150-200 mm). The penetration readings were carried out at 0-200 mm (Table 4.11). In both the surface (0-50 mm) and deeper layers (150-200 mm) there was no effect of the cultivation on the measured soil bulk density (Table 4.11). However the penetration resistance in the surface layer of the right part of the bin decreased from 1.51 to 1.35 MPa, and at 150-200 mm, the penetration resistance in the left part of the bin increased by 0.33 MPa. The mean horizontal force was 1.02 and 1.62 kN while the mean vertical force was 0.35 and 0.67 kN for the left and right part respectively. The width of disturbance was 235 mm, the area of disturbance above the soil surface 0.010 m$^2$ and the maximum height of above ground disturbance 60 mm (Figure 4.13). The area of the soil disturbed below the surface was 0.0175 m$^2$. The force requirements per unit area (specific resistance) were 58.2 and 92.5 kN m$^{-2}$ for the light and dense part respectively (Table 4.12).

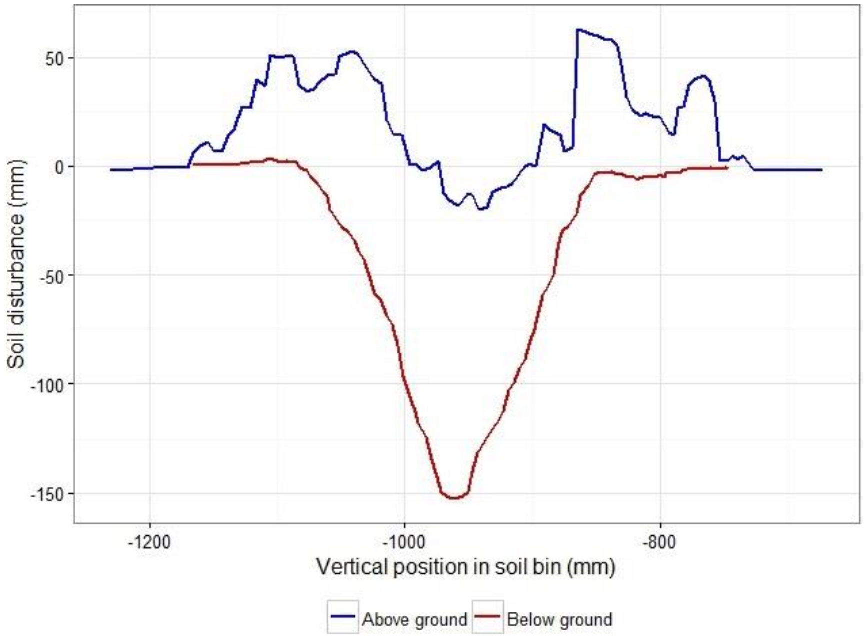


Figure 4.13. Above and below ground disturbance caused by the Claydon working tine

Table 4.12. Summary table of the soil bin results for the Claydon working tine

| Part | Working depth (mm) | Width of disturbance (mm) | Area of soil disturbed (m$^2$) | Horizontal force (kN) | Vertical force (kN) | Specific resistance (kN m$^{-2}$) |
|---|---|---|---|---|---|---|
| Light (left) | 150 | 235 | 0.0175 | 1.02 | 0.35 | 58.2 |
| Dense (right) | 150 | 235 | 0.0175 | 1.62 | 0.67 | 92.5 |

### 4.3.4 Mzuri Pro Til 3

Mzuri Ltd provided their main working leg from the Pro Til 3 for the soil bin tests. The main working tine has a width of 100 mm and a working depth of 150 mm (Table 4.13; Figure 4.14).

Table 4.13. Mzuri tine working depth and geometry

| | Working depth (mm) | Width (mm) | Rake angle in degrees (°) |
|---|---|---|---|
| Tine | 150 | 100.0 | 45 |

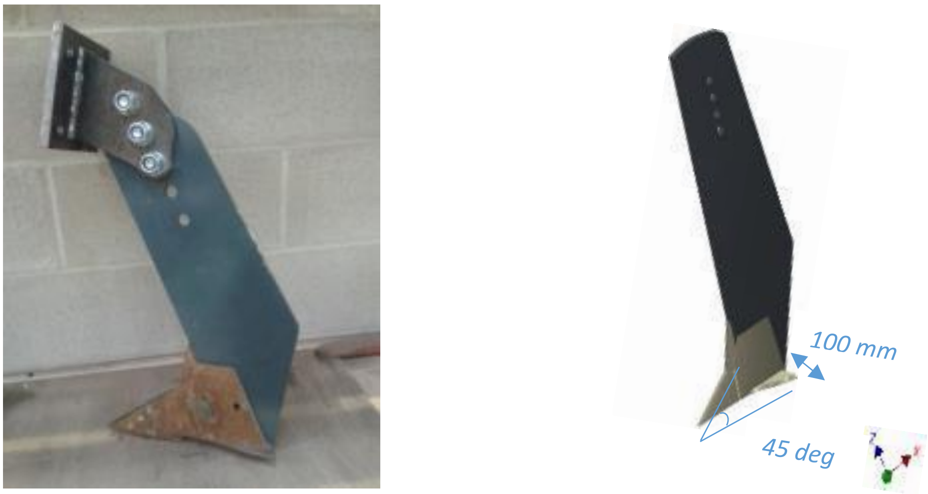


Figure 4.14. Mzuri's working tine left: in the soil bin experiments; right: computer-aided design (CAD) showing its geometry

The soil's surface bulk density was greater on the right part of the bin, and it was not affected by the use of the implement (Table 4.14). However the tine reduced the penetration resistance on the right side of the bin at 150-200 mm, from 3.37 MPa to 2.87 MPa (-0.50 MPa) (Table 4.14).

Table 4.14. Mzuri: mean bulk density and penetration resistance at 0-50 mm and 150-200 mm, alongside force requirements for both parts of the soil bin before and after the runs

| | Left part | | Right part | |
|---|---|---|---|---|
| | Before run | After run | Before run | After run |
| Bulk density (Mg m$^{-3}$) (0-50 mm) | 1.47 b | 1.47 b | 1.56 a | 1.56 a |
| Bulk density (Mg m$^{-3}$) (150-200 mm) | 1.46 b | 1.45 b | 1.53 a | 1.55 a |
| Penetration (MPa) (0-50 mm) | 1.23 b | 1.16 b | 1.71 a | 1.80 a |
| Penetration (MPa) (150-200 mm) | 1.56 c | 1.67 c | 3.37 a | 2.87 b |
| Horizontal force (kN) | 0.77 ab | | 1.20 a | |
| Vertical force (kN) | -0.002 a | | 0.03 a | |

* Means with the same letter are not significantly different (p>0.05) and apply only to rows

The Mzuri, like other implements, showed greater horizontal draught for the right side of the soil bin where, the soil was denser. The tine required a horizontal force of 0.77 kN and 1.20 kN for the light and dense part respectively with the vertical force being almost zero. The resulting above and below ground disturbance was 0.0080 and 0.0217 $m^2$ respectively (Figure 4.15). The width of disturbance was 300 mm and the maximum height of above ground disturbance was 50 mm. For each metre travelled, the Mzuri tine disturbed 0.0217 $m^3$ of soil and its specific resistance was 0.77 / 0.0217 = 35.5 and 1.20 / 0.0217 = 55.3 kN $m^{-2}$ for the light and dense part respectively (Table 4.15).

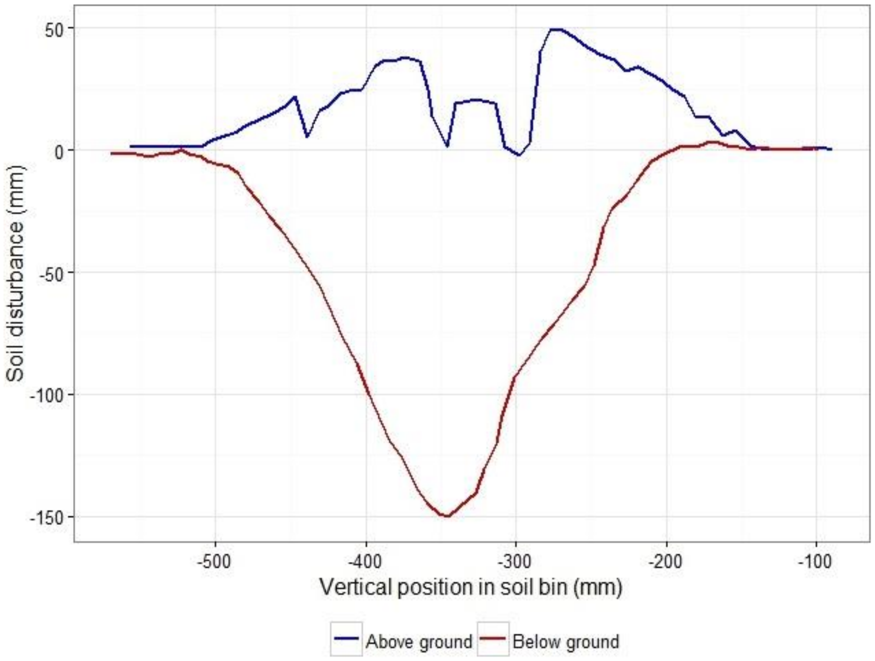


Figure 4.15. Above and below ground disturbance caused by the Mzuri Pro Til 3

Table 4.15. Summary table of the soil bin results for the Mzuri

| Part | Working depth (mm) | Width of disturbance (mm) | Area of soil disturbed ($m^2$) | Horizontal force (kN) | Vertical force (kN) | Specific resistance (kN $m^{-2}$) |
|---|---|---|---|---|---|---|
| Light (left) | 150 | 300 | 0.0217 | 0.77 | -0.002 | 35.5 |
| Dense (right) | 150 | 300 | 0.0217 | 1.20 | 0.03 | 55.3 |

### 4.3.5 Sumo Trio

The Sumo Trio working tine, provided by the Lamport Hall, was that used in the field experiment. The Sumo Trio tine has a width of 215 mm and a working depth of 200 mm (Table 4.16; Figure 4.16).

Table 4.16. Sumo Trio tine working depth and geometry

| | Working depth (mm) | Width (mm) | Rake angle in degrees (°) |
|---|---|---|---|
| Tine | 200 | 215 | 15 |

Figure 4.16. Sumo Trio working tine left: in the soil bin experiments; right: computer-aided design (CAD) showing its geometry

Table 4.17. Sumo Trio: mean bulk density and penetration resistance at 0-50 mm and 150-200 mm, alongside force requirements for both parts of the soil bin before and after the runs

| | *Left part* | | *Right part* | |
|---|---|---|---|---|
| | Before run | After run | Before run | After run |
| Bulk density (Mg $m^{-3}$) (0-50 mm) | 1.44 b | 1.48 b | 1.54 a | 1.54 a |
| Bulk density (Mg $m^{-3}$) (150-200 mm) | 1.46 a | 1.44 a | 1.49 a | 1.52 a |
| Penetration (MPa) (0-50 mm) | 0.95 bc | 0.86 c | 1.33 a | 1.15 ab |
| Penetration (MPa) (150-200 mm) | 1.64 c | 1.80 c | 3.50 a | 2.56 b |
| Horizontal force (kN) | 1.04 a | | 1.45 a | |
| Vertical force (kN) | -0.75 a | | -0.60 a | |

* Means with the same letter are not significantly different ($p>0.05$) and apply only to rows

For both the surface and the tine depth level (0-50 mm and 150-200 mm) there was no influence on soil's bulk density after the implement's run (Table 4.17). However the tine decreased the penetration resistance within the right side of the bin at 150-200 mm from 3.50 to 2.56 MPa. The measured horizontal draught was greater on the right hand side of the bin (1.45 kN) than the left (1.04 kN). The tine required 1.04 and 1.45 kN of horizontal force to pull it through the soil and -0.75 and -0.60 kN vertical force for the light and dense part respectively. The negative sign of the vertical force requirements, indicated good soil penetration as explained in section 4.1. Sumo Trio resulted in 0.0145 and 0.0510 m$^2$ above and below ground disturbance respectively (Figure 4.17). Its width of disturbance was 465 mm and the maximum height of above ground disturbance was 55 mm. For each meter travelled, the volume of below ground soil disturbed was 0.0510 m$^3$. The specific resistance was 28.4 and 20.4 kN m$^{-2}$ for the dense and light part of the soil bin respectively (Table 4.18).

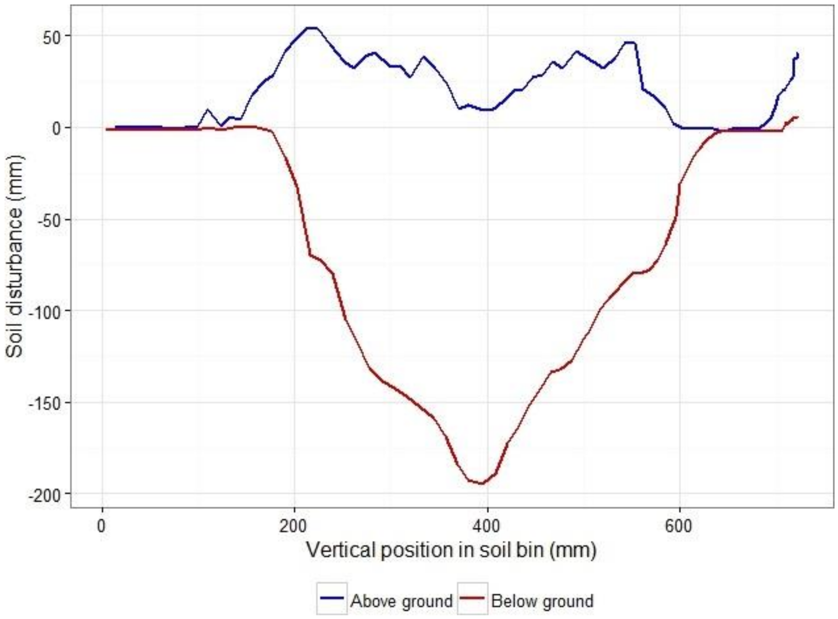


Figure 4.17. Above and below ground disturbance caused by the Sumo Trio

Table 4.18. Summary table of the soil bin results for the Sumo Trio

| Part | Working depth (mm) | Width of disturbance (mm) | Area of soil disturbed (m$^2$) | Horizontal force (kN) | Vertical force (kN) | Specific resistance (kN m$^{-2}$) |
|---|---|---|---|---|---|---|
| Light (left) | 200 | 465 | 0.0510 | 1.45 | -0.60 | 28.4 |
| Dense (right) | 200 | 465 | 0.0510 | 1.04 | -0.75 | 20.4 |

## 4.4 Discussion

The results are firstly discussed in terms of the equipment tested and the design of the soil bin. The results are then discussed in terms of i) forces exerted by the different systems, ii) the effect of working depth, rake angle, and wing design on horizontal force and soil disturbance, iii) the effect on penetration resistance, and iv) the relationship to power requirements.

### 4.4.1 Equipment tested

Ideally, testing of different tillage implements in the soil bin would have used *all* the main components of each tillage treatment. However for most systems, the tests were restricted to working tines, except the Väderstad Seed Hawk where a complete unit was delivered for the tests, and the Claydon which included a working and a seeding tine. The specific measurements reported in this Chapter refer to only the working tine. Appendix B presents the results of the rest of the components for Seed Hawk and Claydon.

### 4.4.2 Soil bin design

A claimed advantage of using the soil bin was to get repeatable measurements. However the density of soil on the right hand side of the bin was typically greater than that on the left hand side. This led to higher penetration resistances for the right than the left hand side. This systematic variability has advantages and disadvantages. Firstly, it increases the range of the tested soil conditions i.e. a dense and a light part of the soil bin. Hence it may be possible to identify soil characteristics vs implement interactions on tillage outcomes. For example in the field experiment, as mentioned in chapter 3, Top Furze was a denser and Snagsborough a lighter field. The disadvantage of the systematic bias was that another factor was introduced in the ANOVA which is the side of the soil bin. Nonetheless that was encountered by including the factor “part of the soil bin” in the statistical calculations.

### 4.4.3 Effect of working depth and rake angle on horizontal draught

The significant low draught value for both the Väderstad Seed Hawk (0.19-0.21 kN) and Rapid (0-08-0.12 kN) can be attributed to their shallow working depth (25 mm) (Table 4.19; Figure 4.18 blue bars). In a similar way, the high draught values for the Claydon, Mzuri and Sumo Trio (0.77 to 1.62 kN) can be attributed to their deeper working depth of 150 and 200 mm respectively whose mean was statistically similar. By contrast the effect of the working width of the base of the tine is less important; for example whilst the working width of the Claydon was only 20 mm, the draught required was similar to that of the Mzuri where the base of the tine had a width of 100 mm.

Table 4.19. Mean draught values for five implements, as described by the part of the soil bin

| | Working Depth | Width | Aspect ratio$^a$ | Rake angle | Draught (kN) | |
|---|---|---|---|---|---|---|
| | (mm) | (mm) | | (°) | Left part of bin | Right part of bin |
| Seed Hawk | 25 | 13.5 | 1.85 :1 | 50 | 0.19 c | 0.21 c |
| Rapid | 25 | | - | - | 0.08 c | 0.12 c |
| Claydon | 150 | 20.0 | 7.50 :1 | 70 | 1.02 ab | 1.62 a |
| Mzuri | 150 | 100 | 1.50 :1 | 45 | 0.77 bc | 1.20 ab |
| Sumo Trio | 200 | 215 | 0.93 :1 | 15 | 1.04 ab | 1.45 ab |

a: Depth to width ratio; *Means with the same letter are not significantly different (p>0.05) and apply to columns

The marginally lower draught of the Mzuri tine (0.77-1.20 kN) as compared to that of the Claydon tine (1.02-1.62 kN) can be attributed to differences in implement geometry. It is argued that a lower rake angle will generally result in a lower horizontal draught (Godwin 2007; Ndisya 2016). The Mzuri tine had a rake angle of 45° as compared to 70° for the Claydon. That was consistent with findings of Ndisya (2016) who mentioned that a rake angle of 45° was found to give the minimum draught requirement while a rake angle of 75° resulted in a high draught requirement. The lowest rake angle (15°) was found at the base of the Sumo Trio tine, and although it was used at a deeper depth (200 mm) than the Claydon and the Mzuri (150 mm), the draught required for the Sumo Trio (1.04-1.45 kN) was similar to that for the Claydon (Table 4.19). The Sumo Trio had the lowest rake angle of the five pieces of implements tested when compared to all the others. Its horizontal draught was almost the same with Claydon's which was working 50 mm shallower. Godwin (2007) results also clearly demonstrated that for low draught and good penetration, implements should be designed with a low rake angle. Furthermore, the similar draught requirements for Sumo Trio when compared to

Claydon is also associated to the effect of critical depth. Claydon 20 mm wide tine with a 70° rake angle, operated at 150 mm. This resulted in an aspect ratio of 7.5 which is above 6.0 where critical depth usually appears. By contrast 215 mm wide tine of Sumo Trio with a rake angle of 15° caused more effective soil loosening as it aspect ratio was around 1 (Table 4.19). As a consequence, Claydon resulted in energy loss at depth which increased its draught requirements.

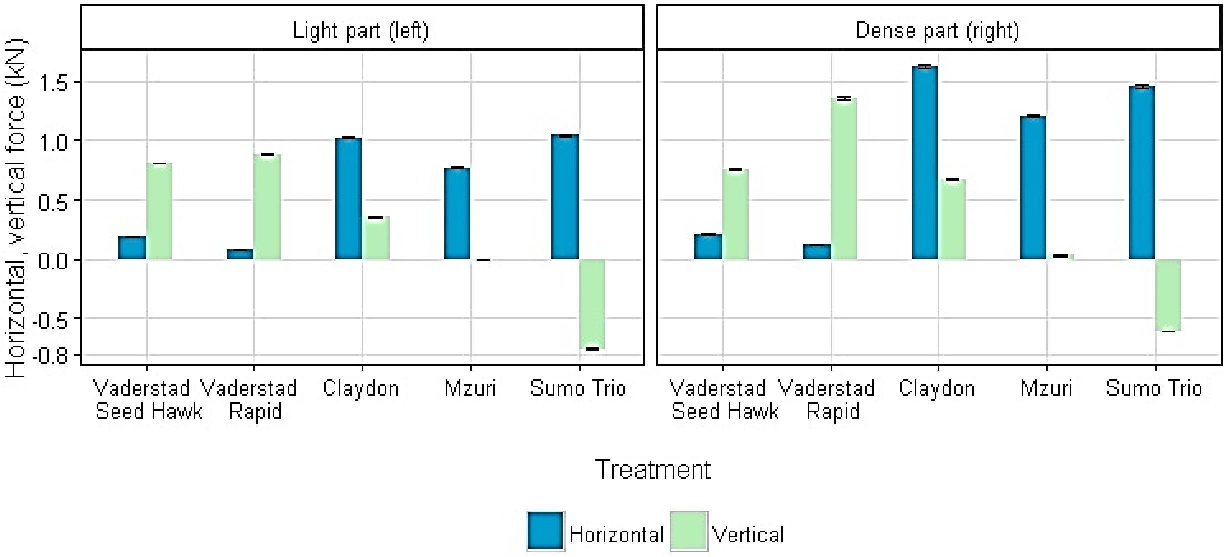


Figure 4.18. Mean horizontal and vertical forces for all the main working implements as separated by the part of the soil bin with standard error of the mean

### 4.4.4 Vertical forces

There were substantial differences between the vertical forces required to operate the five pieces of implements (Figure 4.18; green bars). The Väderstad Seed Hawk and Rapid required downward vertical forces of 0.56-0.65 kN and 0.88-1.35 kN respectively, suggesting poor soil penetration. Within the left part of the bin their values were not statistically different and within the right part were also statistically similar. These forces are a result of the implements' design, as the objective of using the Väderstad Seed Hawk and Rapid is to operate only close to the soil surface level. The Claydon also required a downward force of 0.35-0.67 kN and was statistically similar to Väderstad Seed Hawk and significantly lower than the Väderstad Rapid respectively. By contrast the winged tines with the Mzuri resulted in a minimal and significant greater vertical force (0.00-0.03 kN) as compared to the winged tine of the Sumo Trio. That resulted in an upward negative force of -0.65 to - 0.75 kN (Figure 4.18; green bars) which was the significant lower of all treatments. The above is in agreement with Vozka et al. (2006) who reported that disc implements tend to produce an upward (positive) vertical force preventing penetration as compared to i.e. deep working tines which tend to have downward (negative) vertical forces enabling deep penetration into the soil.

### 4.4.5 Soil disturbance and specific resistance

The soil disturbance measurements highlight the significant lower areas of soil disturbance from Väderstad Seed Hawk and Rapid (Figure 4.19, green lines; Table 4.20) as compared to the deeper implements like Claydon, Mzuri and Sumo Trio. Busari et al. (2015) also found that no-tillage technologies were very effective in reducing soil disturbance. Surface soil disturbance can be important as it can reduce aggregate stability, which in turn can be related to slaking and soil erosion processes. Soil disturbance can also result in a decline in soil biology and this will be examined in Chapter 5.

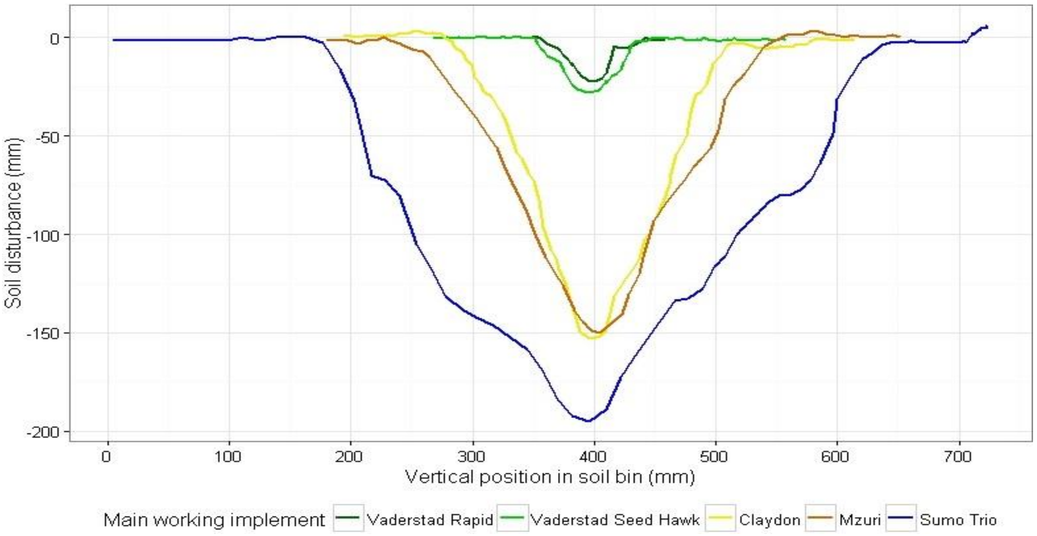


Figure 4.19. Below ground disturbance for all of the main tillage implements

Specific resistance refers to the Draught per cross section of disturbed soil. For the same working depth, winged tines reduced the specific resistance compared to unwinged tines. This was a result of greater below-ground disturbance of the winged tines (i.e. Trio and Mzuri) as compared to non-winged tines like Claydon. This is consistent with Godwin (2007) who reported that winged tines can lower the specific resistance of a plain tine by approximately 10%. The Väderstads had the significant highest specific resistances of all of the tines (Table 4.20). Arvidsson & Hillerström (2010) also reported that specific resistance was much higher for the rigid 80 mm tine than for the mouldboard plough and sweep share.

Table 4.20. Mean values of all the measured properties / characteristics obtained from all the replicates

| | Working depth | Force | | Disturbance | | | Specific Resistance |
|---|---|---|---|---|---|---|---|
| | | Hori-zontal | Vertical | Width | Below ground | Above ground | |
| | (mm) | (kN) | (kN) | (mm) | (m$^2$) | (m$^2$) | (kN m$^{-2}$) |
| V. Seed Hawk | 25 | 0.20 b | 0.778 ab | 83 | 0.0015 d | 0.0027 c | 133 a |
| Rapid | 25 | 0.10 b | 1.114 a | 87 | 0.0009 d | 0.0011 c | 110 ab |
| Claydon | 150 | 1.32 a | 0.493 bc | 235 | 0.0170 bc | 0.0100 ab | 75 b |
| Mzuri | 150 | 0.98 a | 0.014 c | 300 | 0.0210 b | 0.0080 ab | 45 bc |
| Sumo Trio | 200 | 1.24 a | -0.674 d | 465 | 0.0510 a | 0.0145 a | 24 c |

*Means with the same letter are not significantly different ($p>0.05$) and apply to columns

### 4.4.6 Effect of equipment on penetration resistance

In three of the ten runs (considering the left and right sides of the soil bin separately) there was a reduction in the penetration resistance (Table 4.21), and in only one run did the penetration resistance increase.

Table 4.21. Mean penetration resistance values for the five implements through the soil profile (0-100 mm for Väderstads and 0-200 mm for the rest), as described by the part of the soil bin

| | Working Depth (mm) | Width (mm) | Aspect ratio$^a$ (NA) | Rake angle (°) | Penetration resistance (MPa) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Light part (left) | | Dense part (right) | |
| | | | | | Before run | After run | Before run | After run |
| Seed Hawk | 25 | 13.5 | 1.85 :1 | 50 | 1.20 de | 1.04 e | 2.21 cd | 1.71 ef |
| Rapid | 25 | - | - | - | 1.53 bc | 1.38 cd | 1.92 def | 1.57 f |
| Claydon | 150 | 20.0 | 7.50 :1 | 70 | 1.49 bc | 1.67 a | 1.81 de | 1.88 def |
| Mzuri | 150 | 100.0 | 1.50 :1 | 45 | 1.58 ab | 1.54 bc | 2.80 a | 2.54 bc |
| Sumo Trio | 200 | 215.0 | 0.93 :1 | 15 | 1.53 bc | 1.49 c | 2.72 ab | 2.04 de |

*Means with the same letter are not significantly different ($p>0.05$) and apply per part of the soil bin
a: Depth to width ratio

In the right hand side of the soil bin, the Väderstad Seed Hawk reduced the penetrometer resistance from 2.21 MPa to 1.71 MPa (-0.50 MPa). On the same side, the Mzuri reduced the penetration resistance from 2.80 MPa to 2.54 MPa (-0.26 MPa), and the Sumo Trio reduced the resistance from 2.72 MPa to 2.04 MPa (-0.68 MPa). By contrast on the left hand side of the soil bin, the Claydon tine increased the penetrometer readings from 1.49 to 1.67 MPa (+0.18 MPa). Thus in brief, the Claydon straight tine caused an increase in penetrometer readings and the winged tines of Mzuri and Sumo Trio caused a decrease. With regards to bulk density no one of the implements resulted in any change between runs. The above findings support Das et al. (2014) study who concluded that no- and minimum tillage generally reduce penetration resistance at all examined depths. The same study also found that penetration resistance tended to increase with an increase in tillage intensity. That was only in line with the Claydon implement which, had an aspect ratio of 7.5, 70° rake angle and worked slight below critical depth (Table 4.21). By contrast, Mzuri and Sumo Trio which both had lower rake angle and aspect ratio than Claydon, resulted in a decrease in soil penetration resistance between tillage runs. This ties in well with past studies (Godwin 2007; Putte et al. 2012; Masiyandima 1995; Arvidsson 2010) which showed that soil loosening was more effective at depth when tillage implements were wider with low rake angles

### 4.4.7 Scaling up the fuel and power requirements

Using the draught requirements for each component, it is possible to estimate the tractor fuel requirements to draw each tine or disc. As explained in the methodology, the assumptions included a slip efficiency of 0.9, a transmission efficiency of 0.8, a thermal input factor of 3 (personal communication with R. Godwin, 2015) and the specific energy of diesel 38.6 x $10^6$ J $l^{-1}$ (Demirel, 2012). The fuel required to pull a single tine or disc ranged from 0.015-0.022 ml $s^{-1}$ for the Väderstad Rapid to 0.187-0.297 ml $s^{-1}$ for the Claydon (Table 4.22). The number of tines ranges from 6 for the Sumo Trio, 9 for the Mzuri to 15 for the Claydon, and 32 for the Väderstad Seed Hawk and the Rapid. Hence the predicted rate of fuel use required for the Rapid remained the lowest at 0.47-0.70 ml $s^{-1}$, the Seed Hawk rate of fuel use became similar to that for the Mzuri and Sumo Trio (1.12-1.98 ml $s^{-1}$). The highest predicted rate of fuel use was for the Claydon (2.81-4.46 ml $s^{-1}$) (Table 4.22)

Table 4.22. Summary of the energy requirements per piece of equipment

| Treatment | Part | Horizontal force (N) | Velocity (m $s^{-1}$) | Energy required[a] (J $s^{-1}$) | Fuel required per tine[b] (ml $s^{-1}$) | Rows | Fuel required per full set of rows (ml $s^{-1}$) |
|---|---|---|---|---|---|---|---|
| V Seed Hawk | Left | 190 c | 1.7 | 323 c | 0.035 c | 32 | 1.12 |
| | Right | 210 c | 1.7 | 357 c | 0.038 c | 32 | 1.23 |
| V Rapid | Left | 80 c | 1.7 | 136 c | 0.015 c | 32 | 0.47 |
| | Right | 120 c | 1.7 | 204 c | 0.022 c | 32 | 0.70 |
| Claydon | Left | 1020 ab | 1.7 | 1734 ab | 0.187 ab | 15 | 2.81 |
| | Right | 1620 a | 1.7 | 2754 a | 0.297 a | 15 | 4.46 |
| Mzuri | Left | 770 bc | 1.7 | 1309 bc | 0.141 bc | 9 | 1.27 |
| | Right | 1200 ab | 1.7 | 2040 ab | 0.220 ab | 9 | 1.98 |
| Sumo Trio | Left | 1040 ab | 1.7 | 1768 ab | 0.190 ab | 6 | 1.15 |
| | Right | 1450 ab | 1.7 | 2645 ab | 0.266 ab | 6 | 1.60 |

a: the Energy required is the product of the force and the velocity

b: The fuel is assumed to be used with an efficiency of 33.3% and the specific energy of diesel is assumed to be $38.6 \times 10^6$ J $l^{-1}$; *Means with the same letter are not significantly different ($p>0.05$) and apply to rows

Sumner & Williams (2007) reports that the drawbar power needed to pull an implement depends on the ground speed (*V*; kilometers per hour), the draught requirement of the implement (F; *kN*), and a conversion factor (*3.6*) (Equation 4.2).

$$\text{Drawbar power (kW)} = (F \times V) / 3.6 \qquad \text{Eq. (4.2)}$$

Hence, an idea of the minimum tractor drawbar horsepower requirements, to pull the treatments' main implement (all the tines or all the discs) at the above tested speed (6 kph), excluding any other implements like packer wheels or level boards or seeding coulters from the row, are presented in Table 4.23.

As reported by Mileusnić et al. (2010) and Mouazen & Ramon (2002), the shallow treatments resulted in lower draught requirements (and hence calculated fuel requirements per width of equipment). However as demonstrated in Table 4.22 there is a tendency for the shallow equipment to be wider, so that the tractor power requirements remain high.

Table 4.23. The calculated engine power required from a tractor for the tine component of the five pieces of equipment

| | Velocity (kph) | Assumed conversion factor | Draught (kN) | | Assumed drawbar power required by tractor (kW-hp) | |
|---|---|---|---|---|---|---|
| | | | Light part | Dense part | Light part | Dense part |
| V Seed Hawk | 6.0 | 3.6 | 0.19 c | 0.21 c | 10.0 - 13.5 | 11.2 - 15.0 |
| V Rapid | 6.0 | 3.6 | 0.08 c | 0.12 c | 4.26 - 5.71 | 6.40 - 8.57 |
| Claydon | 6.0 | 3.6 | 1.02 ab | 1.62 a | 25.5 - 34.1 | 40.5 - 54.2 |
| Mzuri | 6.0 | 3.6 | 0.77 bc | 1.20 ab | 11.5 - 15.4 | 18.0 - 24.1 |
| Sumo Trio | 6.0 | 3.6 | 1.04 ab | 1.45 ab | 10.4 - 14.0 | 14.5 - 19.5 |

## 4.5 Conclusions

- The soil bin experiment allowed a detailed evaluation of the working tines (and discs) of five of the systems used in the field. The soil bin analysis did not include the full range of components tested in the field, but it focused on only the working tine or disc components.
- There was a systematic bias across the soil bin in that soil density and soil penetration tended to be higher on the right hand side of the bin than the left hand side. The results of both sides are reported separately.
- In general, draught force increased as the density of the soil and the working depth increased. The Väderstad Seed Hawk and Rapid had the lowest horizontal force requirements, the lowest width, area and volume of soil disturbance and the lowest fuel requirements. If these systems result in similar crop yields as the other treatments and have a similar cost, then they should be financially attractive.
- The shallow working Väderstad Seed Hawk and Rapid demanded a high vertical force (0.56-1.35 kN) per tine or disc indicating poor soil penetration. The vertical force requirement for the disc was higher than that for the tine.
- The aspect ratio for Claydon was 7.5. This indicated that the implement was working slightly below critical depth as energy loss is occurring at aspect ratios around 6. That confirmed its increase of penetrometer readings at depth within the light part of the soil bin.
- Mzuri gave lower values for the horizontal draught (and hence fuel requirements) for the same working depth, than the Claydon. This was related to the use of a wing

tine of 100 mm width with a 45° rake angle, while Claydon uses a non-winged tine of 20 mm width and 70° rake angle. The geometry of the Mzuri tine reduces the specific resistance (draught/disturbed area) as compared to Claydon.

- Sumo Trio had the lowest specific resistance of all the implements at 200 mm depth. This was again attributed to the widest winged tine (215 mm) and to its lowest rake angle of 15°. Hence although it was working 50 mm deeper, resulted in 0.17 kN less average horizontal force requirements than the Claydon in the dense part of the soil bin and they were similar in the lighter part.
- At 150 mm depth, energy requirements in terms of fuel per meter of drill rows was significant higher for Claydon (0.297 ml $s^{-1}$) in the right part of the bin as compared to Mzuri Pro Til 3 (0.141 ml $s^{-1}$) for the left part. Sumo Trio and Claydon resulted in statistically similar values (range 0.19-0.29 ml $s^{-1}$) but the latter worked shallower
- Väderstad Seed Hawk and Rapid required the significant lower fuel (0.015-0.038 ml $s^{-1}$) which was statistically similar with one another and with Mzuri within the lighter part of the soil bin (0.141 ml $s^{-1}$).

# 5 TREATMENT EFFECTS ON SOIL CONDITION

## 5.1 Introduction

This chapter presents the results of different tillage treatments on soil properties as measured in the field experiment described in Chapter 3. The tillage treatments were tested in a wheat-oilseed rape rotation in two fields at Lamport Hall in Northamptonshire.

## 5.2 Methodology

The methodology for the measurement of the soil properties are outlined in Chapter 3, but for clarity these are briefly described again. The measurements included soil bulk density, soil penetration resistance, total soil organic carbon and soil microbial biomass carbon, earthworm abundance, available nitrogen, water stable aggregates and soil hydraulic conductivity.

### 5.2.1 Soil bulk density

Measurements of bulk density, as mentioned in section 3.7.3, were taken at 0-50 mm and 150-200 mm in each cropping season within each field (Table 5.1). In 2014 in Snagsborough and in 2015 in both fields, samples were taken before and after tillage. Bulk density is expected to vary with the tillage intensity. As reported in the literature review (Chapter 2), high disturbance treatments generally reduce the soil bulk density as opposed to low disturbance treatments.

Table 5.1. Bulk density measurements for each season, field and time of measurement

| Time of measurement | 2013-14 | | 2014-15 | | 2015-16 | |
|---|---|---|---|---|---|---|
| | SN | TF | SN | TF | SN | TF |
| Before tillage | - | - | 12 Sep 14 | - | 22 Aug 15 | 29 Aug 15 |
| After tillage | 18 May 14 | 13 Apr 14 | 11 Oct 14 | 20 Sep 14 | 20 Sep 15 | 24 Oct 15 |

SN: Snagsborough, TF: Top Furze

Any significant treatment effect on bulk density was determined using analysis of variance (ANOVA) between tillage operations and cropping seasons. Fisher's LSD test was used to separate means at the $p<0.05$ level of significance.

### 5.2.2 Soil penetration resistance and moisture content

Penetrometer readings were carried out on the same dates as the bulk density (Table 5.1) using the Eijkelkamp digital penetrologger. As mentioned in Chapter 3, soil resistance to penetration (PR) was measured three times around each bulk density sampling point, up to a depth of 200 mm from the soil surface. In 2013-14, penetration resistance (PR) was measured after tillage on both fields.  As for bulk density, analysis of variance was also carried out for the difference in penetration resistance before and after tillage as well as between cropping seasons.

Moisture content on the other hand, was measured from the bulk density samples, where the water mass was determined by drying the soil to constant weight and measuring the soil sample mass after and before drying (gravimetric method). The water mass was determined from the difference between the weights of the wet and oven dry samples. There are various studies, as indicated in literature review (Chapter 2), which found that the soil penetration resistance and soil moisture are inversely related

### 5.2.3 Total soil organic carbon

Total soil organic carbon was measured twice: once in the first cropping season (March 2014) and once in the last (March 2016), at two depths (0-50 & 150-20 mm) for both fields using the dry combustion method (elementary analysis). The change in total organic carbon for the different treatments between the cropping seasons was also examined statistically. Total organic carbon was measured in Snagsborough for both depths (0-50 and 150-200 mm) in 2013-14, but only at the surface (0-50 mm) in 2015-16.

### 5.2.4 Soil microbial biomass carbon

Microbial biomass carbon was also measured for each cropping season at 0-50 mm using the fumigation method. Likewise, analysis of variance was also carried out for the difference between cropping seasons.

### 5.2.5 Earthworm abundance

Earthworm abundance, as mentioned in Chapter 3, was measured by digging a 200 mm x 200 mm x 100 mm (width-length-depth) soil pit and counting numbers of earthworms, separated by level of maturity (juveniles or adults) and by ecotypes (i.e. endogeic if they live at the top 100 mm of the soil or anecic if they live deeper). Measurements were carried out within all cropping seasons (except in 2013-14 in Snagsborough). Adults can be distinguished from juveniles as they form a well-developed saddle on their body.

### 5.2.6 Water stable aggregates and soil hydraulic conductivity

The proportion of water stable aggregates for each treatment was determined once a year for all three cropping seasons at 0-100 mm using the wet sieving method. Soil hydraulic conductivity was measured in the second cropping season (2014-15) for both fields using a Decagon mini-disc infiltrometer. The hydraulic conductivity depends on the average size and distribution of pores. In general, tillage treatments which create high porosity (low bulk density), would expect to have the highest hydraulic conductivity.

### 5.2.7 Available nitrogen for plant uptake

Soil nitrogen was measured in its plant available forms. Analysis for the ammonium- $NH_4^+$ and the nitrate- $NO_3^-$ was carried out for all cropping seasons and for both fields using the potassium chloride method. As mentioned in Chapter 2, plants can tie up $NH_4^+$ which is the product of mineralization brought about by soil microorganisms via the breakdown of organic N into plant available forms. In addition, $NH_4^+$ is further transformed by soil microorganisms to nitrate ($NO_3^-$), which is also available to plants. Different tillage treatments that deplete surface residue can also reduce soil microorganisms and organic carbon which in turn can affect the rates of mineralization and finally the nitrogen availability to plants.

## 5.3 Results

### 5.3.1 Soil bulk density

### *5.3.1.1 Snagsborough*

In 2013-14 in Snagsborough (18 May 14), there were no treatment differences in soil bulk density, although values at 0-50 cm (1.25 to 1.35 Mg m$^{-3}$) were generally lower than those (1.32 to 1.37 Mg m$^{-3}$) at 150-200 mm depth (Table 5.2). Values at 0-50 mm and 150-200 mm were similar between treatments. On 12 September 2014 in Snagsborough, immediately before tillage, the soil bulk densities at 0-50 cm in the Väderstad and the Mzuri treatments (1.354-1.368 Mg m$^{-3}$) were greater than those in the Farm system and the Sumo DTS (1.288-1.292 Mg m$^{-3}$) (Table 5.2). By contrast at 150-200 mm depth, the soil bulk densities below the Farm system and the Claydon system (1.414-1.416 Mg m$^{-3}$) were greater than that below the Sumo DTS (1.349 Mg m$^{-3}$) (Table 5.2). After the tillage operation, the soil density in the surface layer (0-50 mm) decreased between September and October in each treatment except the Sumo DTS. The reduction in bulk density in the Väderstad, Farm system, and the Mzuri treatments was greater by 86%, 91% and 55% than that of Sumo DTS respectively (Table 5.2).

Table 5.2. Snagsborough: soil bulk density (Mg m$^{-3}$) mean values at both depths for all sampling dates

| Treatment | After tillage | Before tillage | After tillage | Difference | Before tillage | After tillage | Difference |
|---|---|---|---|---|---|---|---|
| | 18 May 14 | 12 Sep 14 | 11 Oct 14 | Oct-Sept | 22 Aug 15 | 20 Sep 15 | Sep-Aug |
| **0-50 mm** | | | | | | | |
| Farm system | 1.299 a | 1.292 b | 1.169 b | -0.122 b | 1.182 a | 1.171 a | -0.010 ab |
| Claydon | 1.256 a | 1.344 ab | 1.297 a | -0.046 ab | 1.216 a | 1.131 a | -0.085 ab |
| Mzuri | 1.356 a | 1.368 a | 1.319 a | -0.048 b | 1.208 a | 1.154 a | -0.053 ab |
| Sumo DTS | 1.274 a | 1.288 b | 1.339 a | +0.051 a | 1.251 a | 1.132 a | -0.118 b |
| Väderstad | 1.323 a | 1.354 a | 1.284 a | -0.070 b | 1.161 a | 1.178 a | +0.016 a |
| Mean | 1.301 | 1.329 | 1.282 | -0.047 | 1.204 | 1.153 | -0.050 |
| **150-200 mm** | | | | | | | |
| Farm system | 1.370 a | 1.416 a | 1.496 a | +0.080 ab | 1.343 a | 1.334 c | -0.008 b |
| Claydon | 1.334 a | 1.414 a | 1.504 a | +0.089 ab | 1.336 a | 1.395 ab | +0.058 ab |
| Mzuri | 1.324 a | 1.405 ab | 1.507 a | +0.102 a | 1.311 a | 1.426 a | +0.115 a |
| Sumo DTS | 1.369 a | 1.349 b | 1.473 a | +0.124 a | 1.283 a | 1.345 bc | +0.070 ab |
| Väderstad | 1.366 a | 1.369 ab | 1.421 a | +0.025 b | 1.302 a | 1.407 ab | +0.105 a |
| Mean | 1.352 | 1.391 | 1.480 | 0.084 | 1.315 | 1.381 | 0.068 |

*Means with the same letter are not significantly different and apply to columns per depth. Väderstad was replaced by Horsch in Sept 2015

At a depth of 150-200 mm the soil bulk density in October was greater than in September, with the increase in the Sumo DTS and Mzuri being greater than that in the Väderstad treatment. In 2015-16, soil bulk densities were again measured in Snagsborough. In 22-Aug-2015 at the beginning of the new cropping season, the soil bulk densities were similar in each treatment ($p>0.05$). The mean bulk density at 0-50 mm (1.204 Mg $m^{-3}$) was lower than at 150-200 mm (1.315 Mg $m^{-3}$) (Figure 5.1). After the tillage operation, in September 2015, the reduction in the surface bulk density of the Sumo DTS treatment (-0.118 Mg $m^{-3}$) was greater than that observed with the Väderstad which increased its value (+0.016 Mg $m^{-3}$). At a depth of 150-200 mm, soil bulk density in the Farm System (1.334 Mg $m^{-3}$) was less than that in the Väderstad and Mzuri systems (1.407-1.426 Mg $m^{-3}$); the reduction in the soil bulk density from August to September 2015 was greater in the Farm system than the other systems at the same depth (Table 5.2; Figure 5.1).

The changes in bulk density in each treatment can be seen in Figure 5.1. Between 18 May 2014 and 12 September 2014 the bulk densities were relatively consistent. The tillage treatments in late September 2014 generally reduced bulk densities in the surface layer and increased bulk densities at 150-200 mm. However, Sumo DTS increased the soil bulk density at both depths between 12-Sep and 11-Oct-14. In year 3 each treatment again reduced the surface bulk density except the Väderstad. At depth (150-200 mm) each treatment increased the bulk density except the Farm system where a small reduction was noted (Figure 5.1).

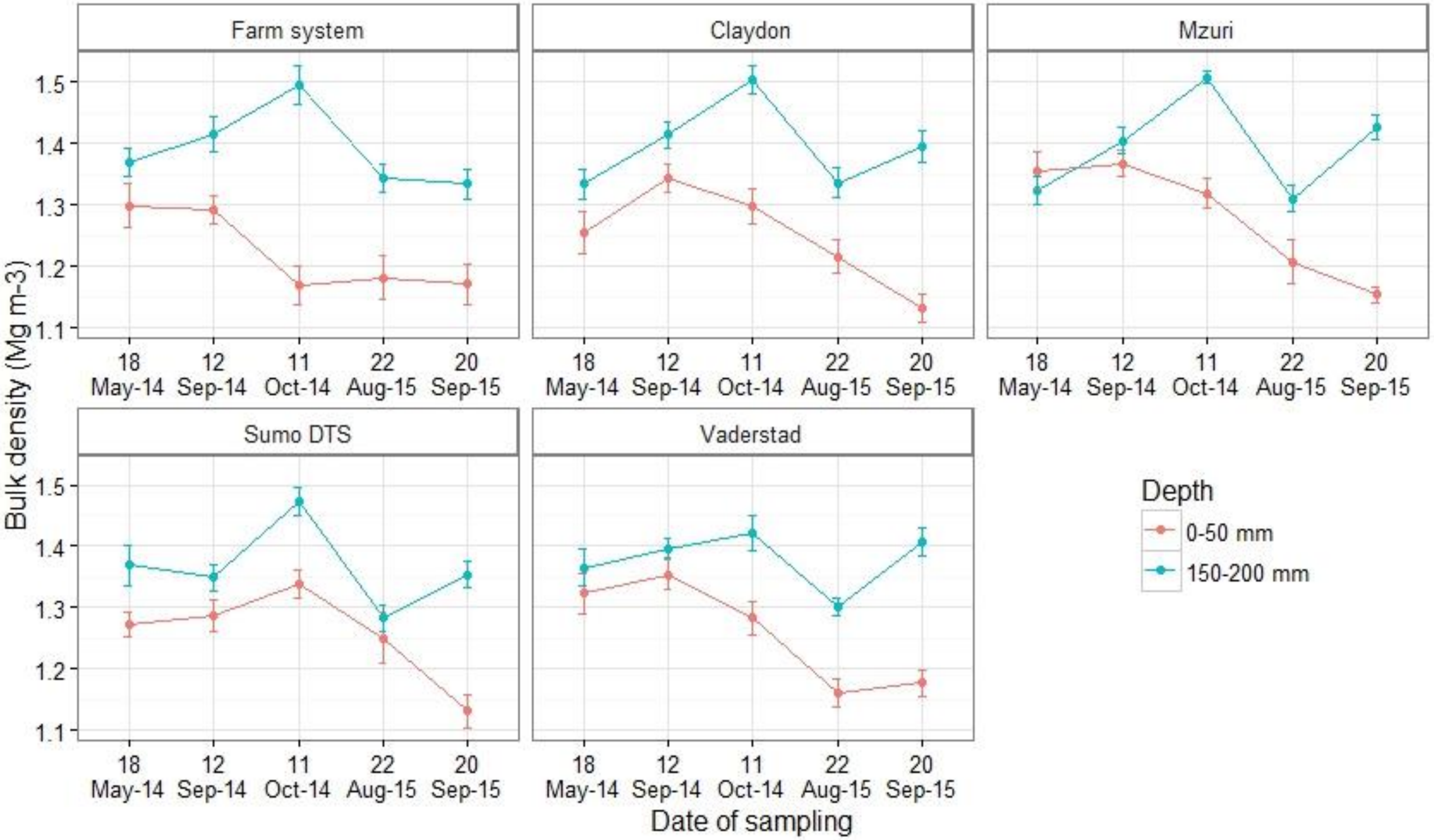


Figure 5.1. Mean bulk density values at the dates of measurements as separated by depth for each treatment with stand error of the mean: Snagsborough (n = 80)

#### 5.3.1.2 Top Furze

In 2013-14 (13-Apr-2014) in Top Furze, there were no significant treatment differences in soil bulk density although values at 0-50 cm (1.296-1.316 Mg m$^{-3}$) tended to be less than those (1.373-1.432 Mg m$^{-3}$) at 150-200 mm (Table 5.3). After tillage on 20 Sep 2014, the soil bulk density at 0-50 mm for the Väderstad and Mzuri which were statistically similar (1.384 and 1.376 Mg m$^{-3}$ respectively) was greater than that for the Farm system (1.248 Mg m$^{-3}$). At 150 - 200 mm depth, the Sumo DTS resulted in a significantly higher bulk density (1.445 Mg m$^{-3}$) than the Farm system (1.355 Mg m$^{-3}$). The Väderstad, Claydon and Mzuri treatments gave statistically similar values (1.394-1.417 Mg m$^{-3}$). In year 3 and before tillage operation (29-Aug-15), the soil bulk density at 150-200 mm was similar in each treatment, but at 0-50 cm, the soil bulk density of the Sumo DTS treatment (1.157 Mg m$^{-3}$) was significantly less than that of Farm system (1.248 Mg m$^{-3}$) (Table 5.3). After tillage (24-Oct-15), the lowest soil bulk density in the surface layer (1.090 Mg m$^{-3}$) was obtained with the Farm System, which had the greatest effect on reducing the bulk density between August and October 2015 as compared to all other treatments. At 150-200 mm, although the Mzuri had the greatest bulk density after tillage, the net change observed in each system, between August and October, was similar.

Table 5.3. Top Furze: soil bulk density (Mg m$^{-3}$) mean values at both depths for all sampling dates

| Treatment | After tillage | After tillage | Before 0.195 | After tillage | Difference |
|---|---|---|---|---|---|
| 0-50 mm | 13 Apr 14 | 20 Sep 14 | 29 Aug 15 | 24 Oct 15 | Oct-Aug |
| Farm system | 1.308 a | 1.248 b | 1.248 a | 1.090 b | -0.157 b |
| Claydon | 1.316 a | 1.332 ab | 1.209 ab | 1.194 a | -0.014 a |
| Mzuri | 1.296 a | 1.376 a | 1.182 ab | 1.199 a | +0.016 a |
| Sumo DTS | 1.304 a | 1.310 ab | 1.157 b | 1.169 a | +0.012 a |
| Väderstad | 1.298 a | 1.384 a | 1.192 ab | 1.162 ab | -0.030 a |
| Mean | 1.304 | 1.330 | 1.198 | 1.163 | -0.035 |
| 150-200 mm | | | | | |
| Farm system | 1.395 a | 1.355 b | 1.316 a | 1.350 ab | +0.034 a |
| Claydon | 1.423 a | 1.416 ab | 1.334 a | 1.372 ab | +0.038 a |
| Mzuri | 1.432 a | 1.394 ab | 1.326 a | 1.408 a | +0.081 a |
| Sumo DTS | 1.384 a | 1.445 a | 1.291 a | 1.371 ab | +0.080 a |
| Väderstad | 1.373 a | 1.417 ab | 1.303 a | 1.337 b | +0.033 a |
| Mean | 1.401 | 1.405 | 1.314 | 1.368 | 0.053 |

*Means with the same letter are not significantly different and apply to columns per depth; Väderstad was replaced by Horsch in Sept 2014

As shown in Figure 5.2, there was a decline in the soil bulk density of each treatment at both depths between 20-Sep-14 (after tillage) and 29-Aug-15 (before tillage). In both fields during the course of the experiment, bulk density values did not overcome the critical value of 1.47 Mg m$^{-3}$ that tend to restrict root growth as mentioned in section 2.4.1.

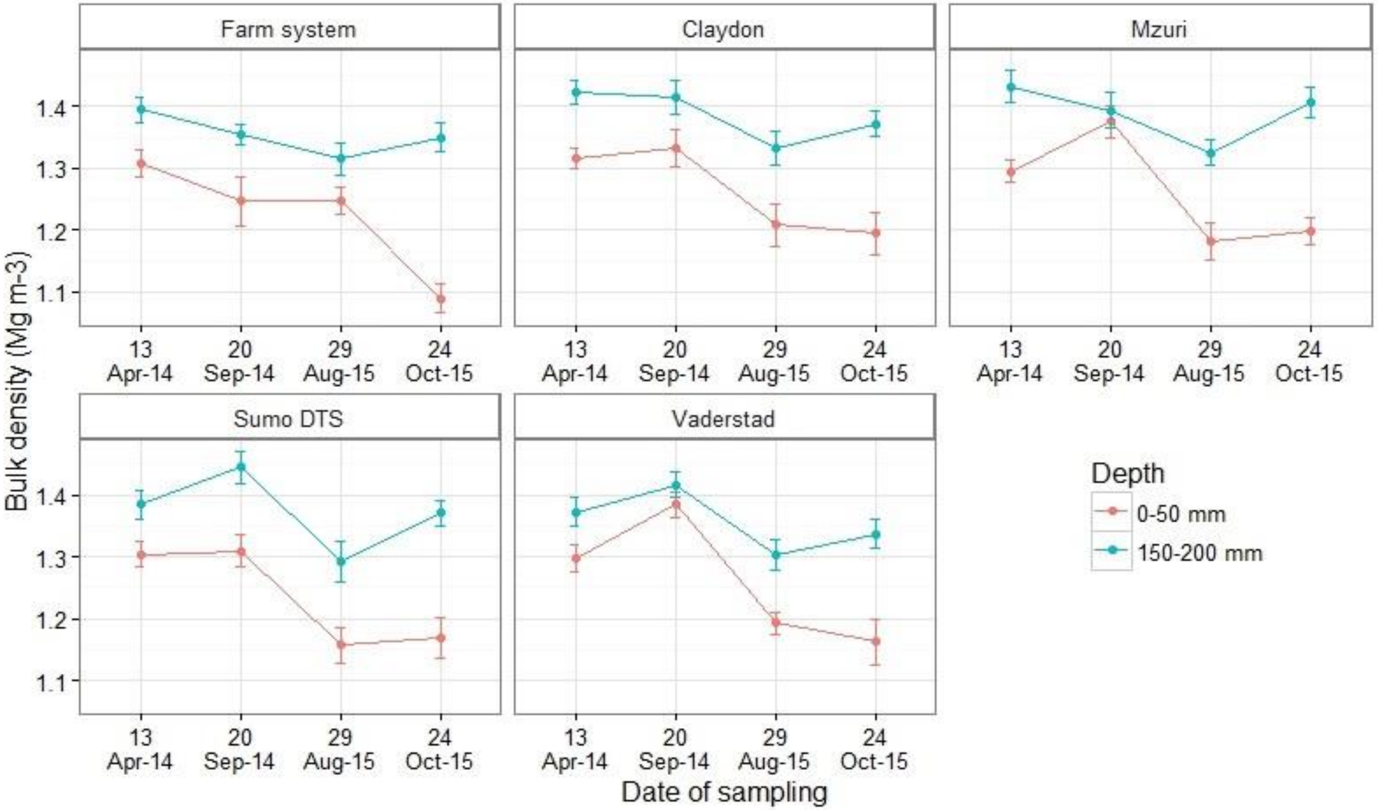


Figure 5.2. Mean bulk density values at the dates of measurements as separated by depth for each treatment with standard error of the mean: Top Furze (n=80)

### 5.3.2 Soil penetration resistance

On 18-May-14 in Snagsborough, the penetration resistance at 0-50 mm was similar for the five treatments (Table 5.4). At 150-200 mm the Väderstad value (2.96 MPa) was higher than that in the other treatments. The penetration resistance occurred in the Mzuri treatment (1.86 MPa) which was lower ($p<0.05$) than for the Sumo DTS (2.41 MPa). In 2014-15, there was no significant ($p>0.05$) difference in the penetration resistance between tillage treatments at 0-50 mm before and after tillage operation. At 150-200 mm although the ANOVA did not show any treatment effect before tillage ($p = 0.06$), the pairwise comparisons (Fischer's test) resulted in a significant higher value for the Farm system and Claydon (2.303-2.253 MPa) compared to Sumo DTS (1.679 MPa). At the same depth the treatments had similar penetration resistances after tillage, but the Sumo DTS showed a greater increase in bulk density (+0.412 MPa) than the Farm system (-0.171 MPa) between 12-Sep and 11-Oct-14 (Table 5.4). In 2015 in Snagsborough at 150-200 mm, the penetration resistance prior to tillage was similar in each treatment (Table 5.4; Figure 5.3).

Table 5.4. Snagsborough: penetration resistance (MPa) mean values at both depths for all sampling dates

| Treatment | After tillage | Before tillage | After tillage | Difference | Before tillage | After tillage | Difference |
|---|---|---|---|---|---|---|---|
| | 18 May 14 | 12 Sep 14 | 11 Oct 14 | Oct-Sept | 22 Aug 15 | 20 Sep 15 | Sep-Aug |
| **0-50 mm** | | | | | | | |
| Farm system | 1.312 a | 1.498 a | 1.271 a | -0.227 a | 0.802 a | 0.595 a | -0.207 a |
| Claydon | 1.202 a | 1.540 a | 1.458 a | -0.082 a | 0.794 a | 0.695 a | -0.099 a |
| Mzuri | 1.179 a | 1.577 a | 1.358 a | -0.219 a | 0.840 a | 0.650 a | -0.190 a |
| Sumo DTS | 1.306 a | 1.303 a | 1.365 a | +0.062 a | 0.773 a | 0.628 a | -0.145 a |
| Väderstad | 1.436 a | 1.490 a | 1.507 a | 0.017 a | 0.844 a | 0.734 a | -0.110 a |
| Mean | 1.287 | 1.481 | 1.391 | -0.089 | 0.810 | 0.660 | -0.150 |
| **150-200 mm** | | | | | | | |
| Farm system | 2.260 bc | 2.303 a | 2.132 a | -0.171 b | 2.121 a | 1.312 c | -0.808 c |
| Claydon | 2.334 bc | 2.253 a | 2.432 a | +0.178 ab | 1.923 a | 2.212 a | +0.288 a |
| Mzuri | 1.865 c | 2.086 ab | 2.201 a | +0.115 ab | 2.280 a | 2.217 a | -0.062 ab |
| Sumo DTS | 2.409 b | 1.679 b | 2.092 a | +0.412 a | 2.126 a | 1.747 b | -0.378 bc |
| Väderstad | 2.962 a | 2.074 ab | 2.351 a | +0.276 ab | 2.158 a | 2.174 a | +0.016 ab |
| Mean | 2.366 | 2.079 | 2.241 | 0.162 | 2.122 | 1.932 | -0.189 |

*Means with the same letter are not significantly different and apply to columns per depth; Väderstad was replaced by Horsch in Sept 2015

However after tillage, the reduction in the penetration resistance of the Farm system (-0.808 MPa), which was statistically similar to the Sumo DTS (-0.378 MPa), was greater than that in all other remaining treatments. In 2013-14 in Top Furze there was no significant treatment effect on penetration resistance at 0-50 mm. However at 150-200 mm the pairwise comparisons showed that the Sumo DTS had higher value (1.567 MPa) than the Farm system (1.251 MPa) (Table 5.5). In 2014-15 in Top Furze, after tillage, the penetration resistance at 150-200 mm depth in the Claydon (2.13 MPa), was similar to that of Mzuri (1.951 MPa), but higher ($p<0.05$) than that for the Sumo DTS and the Farm system (1.560 and 1.357 MPa respectively). In 2015-16 (24-Oct-15), at 0-50 mm the pair comparisons after tillage showed that the Väderstad and Mzuri had a higher penetration resistance (0.708 and 0.697 MPa respectively) than the Farm system (0.508 MPa) although the overall ANOVA showed a $p = 0.143$. All treatments decrease the penetrometer readings between 29-Aug and 24-Oct-15 with the Farm system showing 68% significantly greater decrease (-0.313 MPa) than the Mzuri (-0.098 MPa) (Table 5.5).

Table 5.5. Top Furze: penetration resistance (MPa) mean values at both depths for all sampling dates

| Treatment | After tillage | After tillage | Before tillage | After tillage | Difference |
|---|---|---|---|---|---|
| **0-50 mm** | 13 Apr 14 | 20 Sep 14 | 29 Aug 15 | 24 Oct 15 | Oct-Aug |
| Farm system | 0.578 a | 1.337 a | 0.821 a | 0.508 b | -0.313 b |
| Claydon | 0.721 a | 1.345 a | 0.807 a | 0.645 ab | -0.162 ab |
| Mzuri | 0.693 a | 1.373 a | 0.796 a | 0.697 a | -0.098 a |
| Sumo DTS | 0.705 a | 1.257 a | 0.814 a | 0.626 ab | -0.187 ab |
| Väderstad | 0.731 a | 1.237 a | 0.837 a | 0.708 a | -0.129 ab |
| Mean | 0.685 | 1.309 | 0.815 | 0.636 | -0.177 |
| **150-200 mm** | | | | | |
| Farm system | 1.251 b | 1.357 c | 1.935 a | 1.403 b | -0.532 b |
| Claydon | 1.390 ab | 2.135 a | 1.867 a | 1.794 a | -0.072 a |
| Mzuri | 1.494 ab | 1.951 ab | 1.947 a | 1.879 a | -0.068 a |
| Sumo DTS | 1.567 a | 1.560 c | 1.903 a | 1.680 a | -0.222 ab |
| Väderstad | 1.330 ab | 1.667 bc | 1.845 a | 1.666 a | -0.178 ab |
| Mean | 1.406 | 1.734 | 1.899 | 1.684 | -0.214 |

*Means with the same letter are not significantly different and apply to columns per depth; Väderstad was replaced by Horsch in Sept 2014

Finally, at 150-200 mm the Farm system was associated with a lower penetration (1.40 MPa) than the Mzuri, Claydon, Sumo DTS and Väderstad (1.88, 1.79, 1.68 and 1.66 MPa respectively), which were statistically similar. All treatments were associated with a decrease in penetrometer readings between 29-Aug and 24-Oct-15 with the Farm system showing a greater decrease (-0.532 MPa) than the Claydon and Mzuri (-0.072 and -0.068 respectively) (Table 5.5). At 150-200 mm in Snagsborough between year 1 and 3, the Mzuri resulted in a greater increase in the penetration resistance (+0.35 MPa) than the Farm system (-0.948 MPa), the Sumo DTS (-0.66 MPa) and the Väderstad (-0.78 MPa) (Table 5.6). Between year 2 and 3 at the same depth the Farm system resulted in a greater decrease (-0.820 MPa) than the Claydon and Väderstad (-0.219 and -0.176 MPa) and greater than the Mzuri (+0.016 MPa) (p=0.06). Finally, between 2014-2015 the Väderstad caused a greater reduction in penetration (-0.611 MPa) than the Mzuri and Claydon (0.336 and 0.097 MPa). Between year 1 and 2, in Top Furze the increase in the penetration resistance at 150-200 mm for the Claydon (+0.744 MPa) was greater than in the Farm system and Sumo DTS treatments (+0.106 and -0.007 MPa respectively).

Table 5.6. Change in penetration resistance (MPa) between cropping seasons at 150-200 mm

| Treatment | Snagsborough | | | Top Furze |
|---|---|---|---|---|
| | Change Year 1-3 | Change Year2-3 | Change Year 1-2 | Change Year 1-2 |
| Farm system | -0.948 c | -0.820 b | -0.127 ab | +0.106 b |
| Claydon | -0.122 ab | -0.219 a | +0.097 a | +0.744 a |
| Mzuri | +0.352 a | +0.016 a | +0.336 a | +0.456 ab |
| Sumo DTS | -0.662 bc | -0.345 ab | -0.317 ab | -0.007 b |
| Väderstad | -0.788 bc | -0.176 a | -0.611 b | +0.337 ab |

*Means with the same letter are not significantly different and apply to columns

The change in penetration resistance within all cropping seasons through the whole profile (0-200 mm) in Snagsborough and Top Furze is shown in Figure 5.3 and Figure 5.4. In Snagsborough, each treatment tended to reduce the penetration resistance between year 1 and 3 and there was no relation among penetration resistance and moisture content. In addition, Mzuri increased penetration by 0.352 MPa at 150-200 mm (Table 5.6; Figure 5.3). By contrast in the heavier soil in Top Furze, the general trend was for an increase in penetration resistance from 2013-14 to 2014-15, with a decline from 2014-15 to 2015-16 (Figure 5.4).

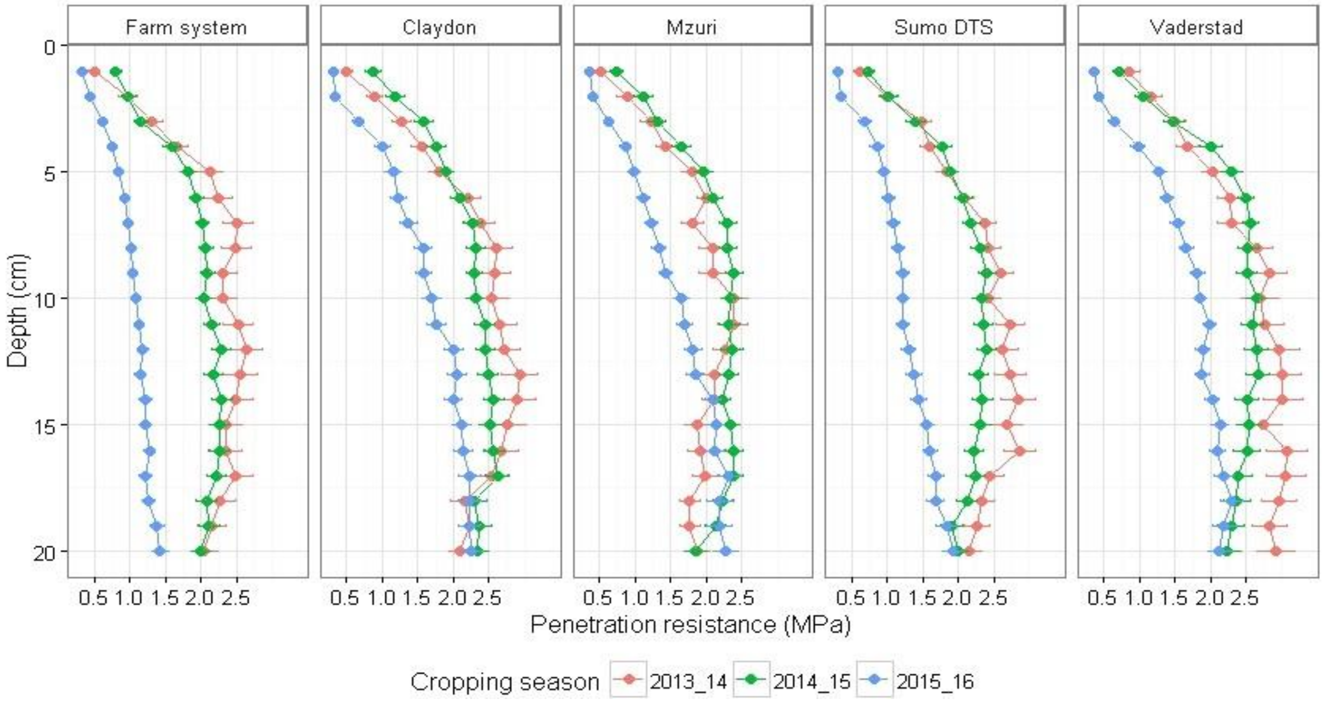


Figure 5.3. Snagsborough: penetration resistance mean values in the soil profile (0-200 mm) by cropping seasons, with standard error of the mean (n = 48)

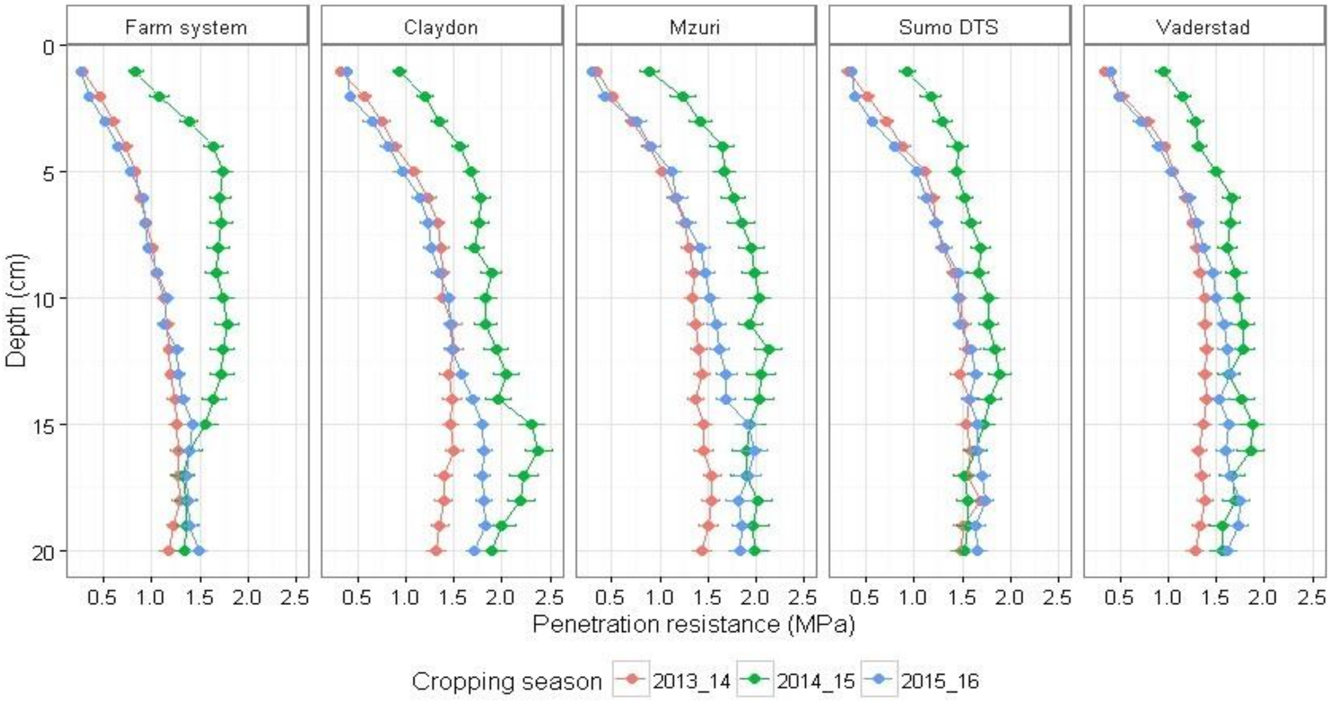


Figure 5.4. Top Furze: penetration resistance mean values in the soil profile (0-200 mm) by cropping seasons, with standard error of the mean (n = 48)

Between year 1 and 2 in Top Furze at 150-200 mm depth there was no relationship among penetration resistance and moisture content. However in the last year there appeared to be a negative relationship between moisture content and penetration resistance (see section 5.3.3). In general soil penetration resistance did not overcome the critical value of 2 MPa that tends to restrict root growth during the course of the experiment. Only in Snagsborough at 150-200 mm depth and within year 1, the penetration values were slightly above 2 MPa.

### 5.3.3 Moisture content

Soil moisture measurements in 18 May 2014 showed no significant difference among the tillage treatments, with values ranging from 18 to 31% in Snagsborough and from 29 to 32% in Top Furze (Table 5.7; Table 5.8). However, in 2014-15 the moisture content differed between treatments. Before tillage in Snagsborough at 0-50 mm depth (12 Sep 14), there was no treatment effect on moisture content at 0-50 mm depth (20-24%), but at 150-200 mm the Väderstad had a significantly higher soil moisture content (23.5%) than the rest of the treatments (19.83-21.26%). At the same depth after tillage (11 Oct 14), a similar response was noted with the Väderstad (24%), being significant higher than the Mzuri (22.1%) and Claydon (22.2%) treatments (Table 5.7). In 22 Aug 15, at 0-50 mm and before tillage, the Mzuri resulted in significantly lower moisture content (22.7%) as compared to the Sumo DTS, Farm system and Väderstad treatments (24.3, 24.6 and 24.7% respectively). In addition, after tillage (20 Sep 15) the Väderstad gave significantly higher soil moisture content at 0-50 mm as compared to the other treatments (26 to 28%). At 150-200 mm, the Farm system was associated with higher moisture content (27%) than all the other treatments (which ranged from 23.9-25.3%).

Table 5.7. Snagsborough: soil moisture content (%) mean values at both depths for all sampling dates

| Treatment | After tillage | Before tillage | After tillage | Difference | Before tillage | After tillage | Difference |
|---|---|---|---|---|---|---|---|
| | 18 May 14 | 12 Sep 14 | 11 Oct 14 | Oct-Sep | 22 Aug 15 | 20 Sep 15 | Sep-Aug |
| 0-50 mm | | | | | | | |
| Farm system | 30.84 a | 21.23 a | 30.65 a | +7.99 a | 24.66 a | 28.20 b | +3.54 bc |
| Claydon | 27.12 a | 21.26 a | 26.57 bc | +5.31 a | 23.36 ab | 27.27 bc | +3.91 b |
| Mzuri | 26.47 a | 20.30 a | 26.11 c | +5.80 a | 22.69 b | 26.19 c | +3.50 bc |
| Sumo DTS | 27.39 a | 24.07 a | 26.12 c | +4.67 a | 24.34 a | 26.02 c | +1.68 c |
| Väderstad | 26.94 a | 22.15 a | 29.73 ab | +7.58 a | 24.75 a | 30.82 a | +6.07 a |
| Mean | 27.75 | 21.80 | 27.84 | 6.27 | 23.96 | 27.70 | +3.74 |
| 150-200 mm | | | | | | | |
| Farm system | 18.23 a | 21.14 b | 23.57 ab | +2.42 a | 21.39 ab | 27.04 a | +5.65 a |
| Claydon | 18.24 a | 20.63 b | 22.24 bc | +1.60 a | 20.94 ab | 25.26 b | +4.32 ab |
| Mzuri | 18.08 a | 19.83 b | 22.11 c | +2.27 a | 20.58 b | 24.71 b | +4.13 ab |
| Sumo DTS | 19.33 a | 21.26 b | 23.08 abc | +1.81 a | 21.76 a | 25.39 b | +3.63 bc |
| Väderstad | 20.02 a | 23.51 a | 23.97 a | +0.46 a | 21.64 a | 23.98 b | +2.34 c |
| Mean | 18.78 | 21.27 | 22.99 | 1.71 | 21.26 | 25.28 | +4.01 |

*Means with the same letter are not significantly different and apply to columns per depth; Väderstad was replaced by Horsch in Sept 2015

The change in moisture content with the Väderstad (+6.07%) between September and August 2015 was greater than in the other treatments (1.68-3.91%) while at depth the Farm system resulted in a significantly higher increase in moisture (+5.65%) than Sumo DTS and Väderstad (3.63-2.34%). On 20 September 14 in Top Furze, the Mzuri had a significantly lower soil moisture content (24.3%) than the Väderstad and Farm system (27.45-26.96%) at the surface level (0-50 mm) (Table 5.8). A similar response was observed at 150-200 mm, with the Mzuri and Claydon (23.1-24.93%) having a significant lower moisture content than the Farm system (27.1%). In 2015-16, the soil moisture at a depth of 0-50 mm was similar in each of the treatments, both in 29 Aug and 24 Oct 15. However at 150-200 mm depth, the Sumo DTS had a significant higher moisture content that the Claydon before tillage, whereas after tillage the moisture content within the Farm system (32.5%) was significantly greater than the other treatments (28.2-30.0%) (Table 5.8). No treatment effect on soil moisture was noted at the change between October and August at 0-50 mm level, but at depth the Farm system was associated with greater increase in the soil moisture content (+2.29%) than the Mzuri and Sumo DTS (+0.09 and -1.37%). In most cases the high moisture contents were associated with low penetrometer readings (Table 5.4-Table 5.7 and Table 5.5-Table 5.8).

Table 5.8. Top Furze: soil moisture content (%) mean values at both depths for all sampling dates

| Treatment | After tillage | After tillage | Before tillage | After tillage | Difference |
|---|---|---|---|---|---|
| 0-50 mm | 13 Apr 14 | 20 Sep 14 | 29 Aug 15 | 24 Oct 15 | Oct-Aug |
| Farm system | 29.16 a | 26.96 a | 31.64 a | 34.10 a | +2.46 a |
| Claydon | 31.56 a | 26.41 ab | 31.74 a | 33.19 a | +1.45 a |
| Mzuri | 31.35 a | 24.30 b | 30.76 a | 32.72 a | +1.96 a |
| Sumo DTS | 29.32 a | 25.89 ab | 32.07 a | 34.22 a | +2.15 a |
| Väderstad | 32.09 a | 27.45 a | 32.93 a | 34.01 a | +1.08 a |
| Mean | 30.70 | 27.21 | 31.83 | 33.65 | +1.82 |
| 150-200 mm | | | | | |
| Farm system | 31.70 a | 27.17 a | 30.17 ab | 32.46 a | +2.29 a |
| Claydon | 30.03 a | 24.93 bc | 27.98 b | 29.38 b | +1.40 ab |
| Mzuri | 30.05 a | 23.15 c | 28.10 ab | 28.20 b | +0.09 bc |
| Sumo DTS | 31.14 a | 25.25 ab | 30.27 a | 28.89 b | -1.37 c |
| Väderstad | 30.58 a | 25.56 ab | 28.95 ab | 30.03 b | +1.08 ab |
| Mean | 30.70 | 25.21 | 29.09 | 29.79 | +0.70 |

*Means with the same letter are not significantly different and apply to columna per depth; Väderstad was replaced by Horsch in Sept 2014

In Top Furze in year 3 the linear regression analysis (Equation 5.1) showed a negative significant effect of soil moisture content on penetration resistance (PR) ($R^2 = 0.30$; n = 80; `*p<0.1; **p<0.05; ***p<0.01)`).

$$PR = -0.05\ (\pm 0.01)^{**}\ \text{Moisture content} + 3.1\ (\pm 0.3)^{***} \qquad \text{Eq. (5.1)}$$

Equation 5.1 suggests that for every 10% increase on soil moisture content, the soil's resistance to penetration is to decrease by 0.5 MPa. A similar negative significant effect was also noticed in Snagsborough within the second year. In the rest of years and within each field there was no relation between moisture content and penetration resistance.

### 5.3.4 Total soil organic carbon

In year 1 at surface level (0-50 mm), the ANOVA did not show any significant treatment effect (p=0.40), but the pairwise comparisons (Fischer's test) concluded that the Farm system (2.7%) had greater soil organic carbon than the Mzuri (2.5%).

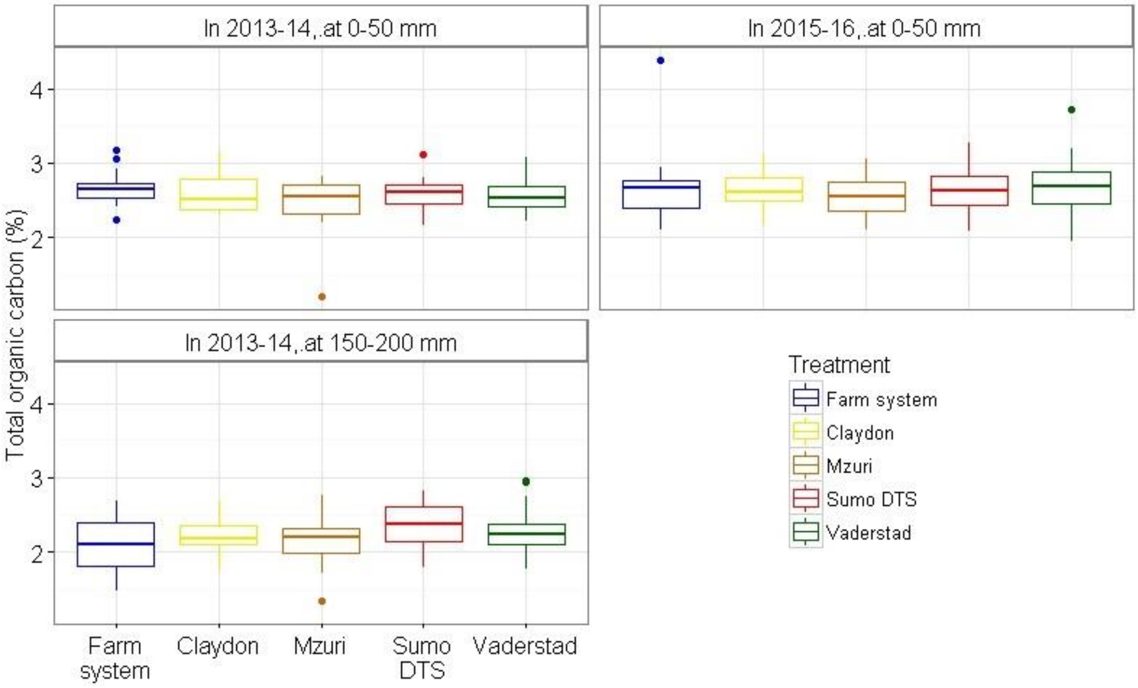


Figure 5.5. Total organic carbon by cropping season in Snagsborough at both depths. Boxplot shows the spread of the data set (box = 25-75% of the data, line within box = median value, upper whisker = upper 25% of the data, lower whisker = lower 25% of the data) (n=16).

Within the same year at 150-200 mm the mean organic carbon value of 2.3% for the Sumo DTS, which was statistically similar to the Claydon and Väderstad treatments (2.2%) was greater (p<0.05) than that of the Farm system and Mzuri (2.1%) (Figure 5.5; Table 5.9). At surface level in year 3 no significant effect was noted. Between year 3 and 1 at 0-50 mm all treatments showed a statistically similar increase in soil organic carbon ranging from +0.10% for the Väderstad to +0.03% for the Farm system (p=0.65) (Table 5.9).

Table 5.9. Snagsborough mean values of total organic carbon (%) per depth and cropping season

| **0-50 mm** | In 2013-14 | In 2015-16 | Difference |
|---|---|---|---|
| Farm system | 2.664 a | 2.690 a | + 0.027 a |
| Claydon | 2.574 ab | 2.636 a | + 0.061 a |
| Mzuri | 2.459 b | 2.544 a | + 0.084 a |
| Sumo DTS | 2.584 ab | 2.631 a | + 0.047 a |
| Väderstad | 2.581 ab | 2.686 a | + 0.105 a |
| Mean | 2.572 | 2.637 | +0.065 |
| **150-200 mm** | | | |
| Farm system | 2.119 c | - | - |
| Claydon | 2.217 abc | - | - |
| Mzuri | 2.147 bc | - | - |
| Sumo DTS | 2.348 a | - | - |
| Väderstad | 2.289 ab | - | - |
| Mean | 2.224 | | |

*Means with the same letter are not significantly different and apply to columns per depth; Väderstad was replaced by Horsch in 2015-16

In Top Furze within year 1, there was no significant treatment effect on soil organic carbon at both depths. Within year 3, the analysis of variance did not pick up any significant effect at both depths (p=0.17). However at 0-50 mm the pairwise Fischer's comparisons did conclude that Väderstad belonged higher organic carbon (2.9%) than the Farm system and Sumo DTS (2.7-2.7%) while at 150-200 mm the Farm system resulted in greater value (2.599%) than the Claydon (2. 4%) (Table 5.10). In Top Furze there was also a trend for the total soil organic carbon to increase at 0-50 mm during the course of the experiment (Figure 5.6; Table 5.10).

Between 2013-14 and 2015-16, the total soil organic carbon at 0-50 mm increased significantly more (p<0.05) with the Väderstad (+0.408%) and the Mzuri treatments (+0.389%) than the Sumo DTS and Farm system (+0.102 and +0.079%) (Table 5.10). At depth (150-200 mm) the change between seasons was not significantly different. Finally, there was also a significant difference (p<0.05) in total soil organic carbon between the two measured depths for both fields, with the deeper soil (150-200 mm) having less total organic carbon than the surface layer (0-50 mm) in all cases.

Table 5.10. Total organic carbon changes (%) between cropping seasons at both depths in Top Furze

| Top Furze | | | |
|---|---|---|---|
| **0-50 mm** | In 2013-14 | In 2015-16 | Difference |
| Farm system | 2.631 a | 2.710 b | + 0.079 b |
| Claydon | 2.594 a | 2.789 ab | + 0.195 ab |
| Mzuri | 2.439 a | 2.829 ab | + 0.389 a |
| Sumo DTS | 2.611 a | 2.714 b | + 0.102 b |
| Väderstad | 2.577 a | 2.985 a | + 0.408 a |
| Mean | 2.570 | 2.805 | +0.234 |
| **150-200 mm** | | | |
| Farm system | 2.335 a | 2.599 a | + 0.264 a |
| Claydon | 2.312 a | 2.394 b | + 0.082 a |
| Mzuri | 2.312 a | 2.543 ab | + 0.231 a |
| Sumo DTS | 2.346 a | 2.475 ab | + 0.128 a |
| Väderstad | 2.413 a | 2.550 ab | + 0.137 a |
| Mean | 2.344 | 2.512 | +0.168 |

*Means with the same letter are not significantly different and apply to columns per depth

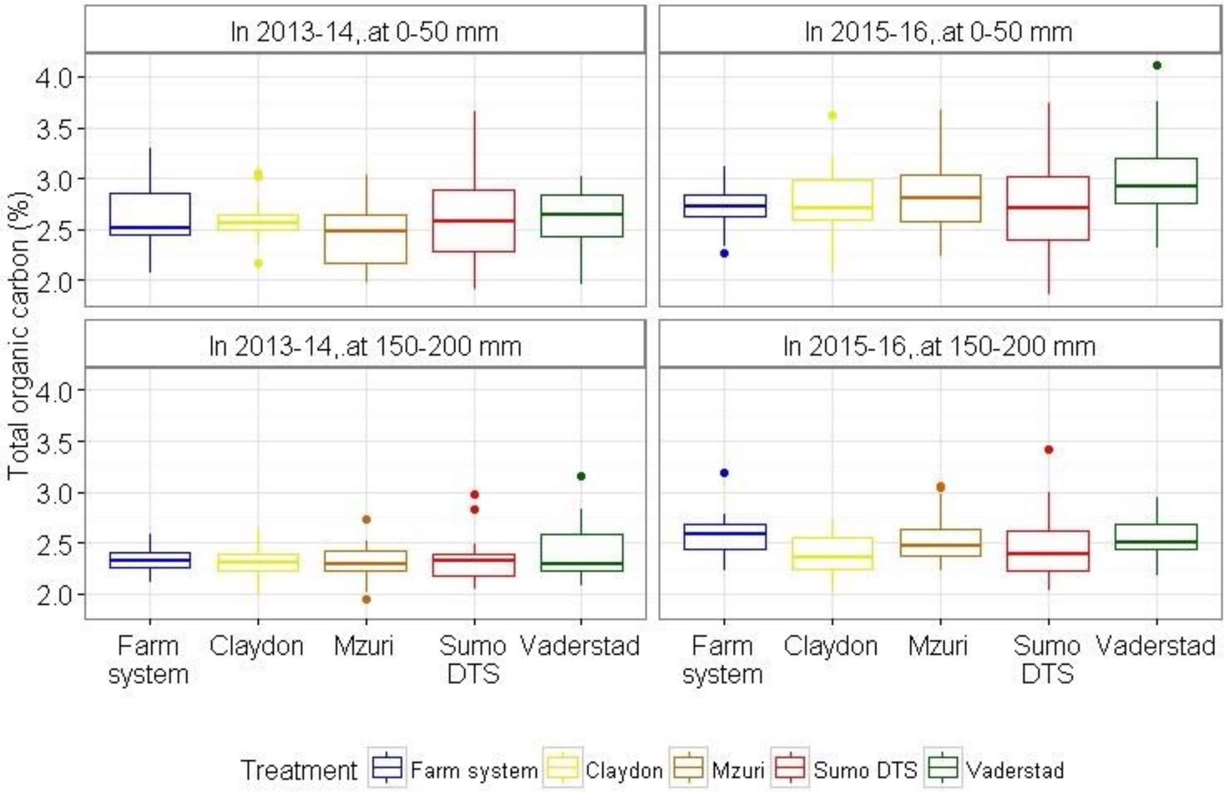


Figure 5.6. Total organic carbon content by cropping season in Top Furze at both depths. Boxplot shows the spread of the data set (box = 25-75% of the data, line within box = median value, upper whisker = upper 25% of the data, lower whisker = lower 25% of the data) (n=16).

Table 5.11. Mean bulk density (BD; units: Mg m$^{-3}$), total organic carbon (TOC; units %) and carbon stocks (C_Stokes; units: t C ha$^{-1}$) between year 1 and 3 in Snagsborough at 0-50 mm

| | 2013-14 | | | 2015-16 | | | Difference |
|---|---|---|---|---|---|---|---|
| **0-50 mm** | BD | TOC | C_Stocks | BD | TOC | C_Stocks | C_Stocks |
| Farm system | 1.299 a | 2.664 a | 17.256 a | 1.171 a | 2.690 a | 15.729 a | -1.526 a |
| Claydon | 1.256 a | 2.574 ab | 16.203 a | 1.131 a | 2.636 a | 14.895 a | -1.307 a |
| Mzuri | 1.356 a | 2.459 b | 16.820 a | 1.154 a | 2.544 a | 14.639 a | -2.180 a |
| Sumo DTS | 1.274 a | 2.584 ab | 14.468 a | 1.132 a | 2.631 a | 14.854 a | -1.614 a |
| Väderstad | 1.323 a | 2.581 ab | 17.161 a | 1.178 a | 2.686 a | 15.766 a | -1.394 a |
| Mean | 1.302 | 2.572 | 16.381 | 1.153 | 2.637 | 15.176 | -1.604 |
| **150-200 mm** | | | | | | | |
| Farm system | 1.370 a | 2.119 c | 14.496 bc | 1.334 c | - | - | - |
| Claydon | 1.334 a | 2.217 abc | 14.808 abc | 1.395 ab | - | - | - |
| Mzuri | 1.324 a | 2.147 bc | 14.167 c | 1.426 a | - | - | - |
| Sumo DTS | 1.369 a | 2.348 a | 16.080 a | 1.345 bc | - | - | - |
| Väderstad | 1.366 a | 2.289 ab | 15.745 ab | 1.407 ab | - | - | - |
| Mean | 1.352 | 2.224 | 15.059 | 1.381 | - | - | - |

*Means with the same letter are not significantly different and apply to columns per depth; Väderstad was replaced by Horsch in 2015-16

Table 5.12. Mean bulk density (BD; units: Mg m$^{-3}$), total organic carbon (TOC; units %) and carbon stocks (C_Stokes; units: t C ha$^{-1}$) between year 1 and 3 in Top Furze at 0-50 mm and 150-200 mm

| | 2013-14 | | | 2015-16 | | | Difference |
|---|---|---|---|---|---|---|---|
| **0-50 mm** | BD | TOC | C_Stocks | BD | TOC | C_Stocks | C_Stocks |
| Farm system | 1.308 a | 2.631 a | 17.191 a | 1.090 b | 2.710 b | 14.738 b | - 2.452 c |
| Claydon | 1.316 a | 2.594 a | 17.064 a | 1.194 a | 2.789 ab | 16.583 a | - 0.481 ab |
| Mzuri | 1.296 a | 2.439 a | 15.740 a | 1.199 a | 2.829 ab | 16.854 a | + 1.113 a |
| Sumo DTS | 1.304 a | 2.611 a | 16.974 a | 1.169 a | 2.714 b | 15.850 ab | -1.124 bc |
| Väderstad | 1.298 a | 2.577 a | 16.741 a | 1.162 ab | 2.985 a | 17.229 a | + 0.487 ab |
| Mean | 1.304 | 2.570 | 16.742 | 1.163 | 2.805 | 16.250 | -0.491 |
| **150-200 mm** | | | | | | | |
| Farm system | 1.395 a | 2.335 a | 16.286 a | 1.350 ab | 2.599 a | 17.536 a | + 1.249 a |
| Claydon | 1.423 a | 2.312 a | 16.449 a | 1.372 ab | 2.394 b | 16.407 a | -0.042 a |
| Mzuri | 1.432 a | 2.312 a | 16.534 a | 1.408 a | 2.543 ab | 17.862 a | + 1.327 a |
| Sumo DTS | 1.384 a | 2.346 a | 16.194 a | 1.371 ab | 2.475 ab | 16.979 a | + 0.785 a |
| Väderstad | 1.373 a | 2.413 a | 16.518 a | 1.337 b | 2.550 ab | 17.058 a | + 0.539 a |
| Mean | 1.401 | 2.344 | 16.396 | 1.368 | 2.512 | 17.168 | + 0.771 |

*Means with the same letter are not significantly different and apply to columns per depth

Soil organic carbon stocks can be estimated given the treatments' bulk density and organic carbon content provided that they both refer to the same sampling depth. In Snagsborough at surface level there were no significant treatment effects on carbon stocks in both years. However, the Farm system was top ranked in year 1 (17.25 t C ha$^{-}$

$^{1}$) and the Farm system and Väderstad were top ranked (15.73-15.76 t C ha$^{-1}$) in year 3 (Table 5.11). At 150-200 mm depth Sumo DTS and Väderstad resulted in greater ($p<0.05$) carbon stocks (16.08-15.74 t C ha$^{-1}$) than the Mzuri (14.16 t C ha$^{-1}$). In Top Furze carbon stocks were also similar between treatments in year one at both depths, but ANOVA showed a significant treatment effect at 0-50 mm in year 3 (Table 5.12). The Farm system had a significant lower value of 14.74 t C ha$^{-1}$ than the Väderstad, Mzuri and Claydon (17.30, 16.85, 16.58 t C ha$^{-1}$). It is apparent though (Table 5.12), that the increase in the carbon stock of the Väderstad and Mzuri between year 1 and 3 (+0.48 and +1.11 t C ha$^{-1}$) was significantly greater than the decrease observed with the Farm system (-2.45 t C ha$^{-1}$). At depth (150-200 mm) within the same field no significant change was noted.

### 5.3.5 Soil microbial biomass carbon

Soil microbial biomass carbon was measured within all cropping seasons at 0-50 mm. The analysis of variance showed no significant treatment effect for the two last seasons (2014-15 and 2015-16) for both fields (p=0.15-0.35) but some pairwise comparisons did show differences. Even not significant the microbial biomass carbon in Snagsborough in year 3 was higher in Väderstad than the Mzuri and the change between year 1 and 3, was also greater in Väderstad compared to Mzuri (Table 5.13).

Table 5.13. Mean microbial biomass carbon (µg C g soil$^{-1}$) along with changes between years in Snagsborough

| Treatment | Years | | | Difference | | |
|---|---|---|---|---|---|---|
| | Year 1 | Year 2 | Year 3 | Year 1-2 | Year 1-3 | Year 2-3 |
| Farm system | 424 a | 590 a | 502 ab | +167 a | +78 ab | -89 a |
| Claydon | 406 a | 592 a | 497 ab | +186 a | +91 ab | -95 a |
| Mzuri | 443 a | 607 a | 478 b | +164 a | +35 b | -129 a |
| Sumo DTS | 448 a | 584 a | 520 ab | +135 a | +72 ab | -63 a |
| Väderstad | 407 a | 623 a | 550 a | +216 a | +143 a | -73 a |
| Mean | 425 | 599 | 509 | +174 | +84 | -90 |

*Means with the same letter are not significantly different and apply to columns; Year 1: 2013-14, Year 2:2014-15, Year 3:2015-16; Väderstad was replaced by Horsch in 2015-16

Table 5.14. Mean microbial biomass carbon (μg C g soil$^{-1}$) along with changes between years in Top Furze

| Treatment | Years | | | Difference | | |
|---|---|---|---|---|---|---|
| | Year 1 | Year 2 | Year 3 | Year 1-2 | Year 1-3 | Year 2-3 |
| Farm system | 339 b | 397 a | 310 b | +58 a | -30 a | -87 a |
| Claydon | 322 b | 400 a | 321 b | +78 a | -1 a | -79 a |
| Mzuri | 380 ab | 356 a | 361 ab | -24 a | -19 a | +5 a |
| Sumo DTS | 380 ab | 413 a | 364 ab | +33 a | -16 a | -48 a |
| Väderstad | 444 a | 425 a | 418 a | -19 a | -26 a | -7 a |
| Mean | 373 | 398 | 355 | +25 | -18 | -43 |

*Means with the same letter are not significantly different and apply to columns; Year 1: 2013-14, Year 2:2014-15, Year 3:2015-16; Väderstad was replaced by Horsch in 2014-15

In general in Snagsborough the MBC increased from year 1 to year 2, while a decrease was noted between year 2 and 3 (Table 5.13). The only case that was associated with a significant treatment effect (p=0.001) was in Top Furze in 2013-14. The level of microbial biomass in the Väderstad treatment (444 μg C g soil$^{-1}$) was greater than that in the Claydon and Farm system (322 and 339 μg C g soil$^{-1}$ respectively) (Table 5.14). The last year showed a similar pattern to year 1 but the ANOVA did not show any significant effect (p=0.35) (Table 5.14).

### 5.3.6 Earthworm abundance

Earthworms were monitored in both fields and results refer to their numbers and biomass (g m$^{-2}$). Their numbers refer to juveniles, adults and total per ecotype. Earthworms were monitored in 2014-15 and 2015-16 for Snagsborough and in all cropping seasons in Top Furze. For Snagsborough the analysis of variance showed that in 2014-15 both juveniles and adults were significantly higher under the Väderstad (156 and 36 m$^{-2}$) as compared to the other treatments for the endogeic ecotype (Figure 5.7). A similar response was also observed in 2015-16 and for endogeic species, with the Väderstad treatment having a significantly higher number of juveniles, adults and juveniles plus adults (p<0.05) than the other treatments (Figure 5.7). For the deeper worms (anecic) no treatment effect was apparent for either juveniles or adults. In terms of their combined numbers per ecotype, the endogeic were significantly more abundant in the Väderstad treatment (192 m$^{-2}$) than all other treatments. Sumo DTS and Farm system had similar values (105 and 97 m$^{-2}$) which were significantly higher than that in the Mzuri and Claydon treatments (61 and 50 m$^{-2}$). The anecic numbers of worms (juveniles + adults) for the Väderstad (36 m$^{-2}$) were similar to Sumo DTS and Mzuri (27 and 25 m$^{-2}$), but significant greater than the Farm system and Claydon (19 and 13) (Figure 5.7).

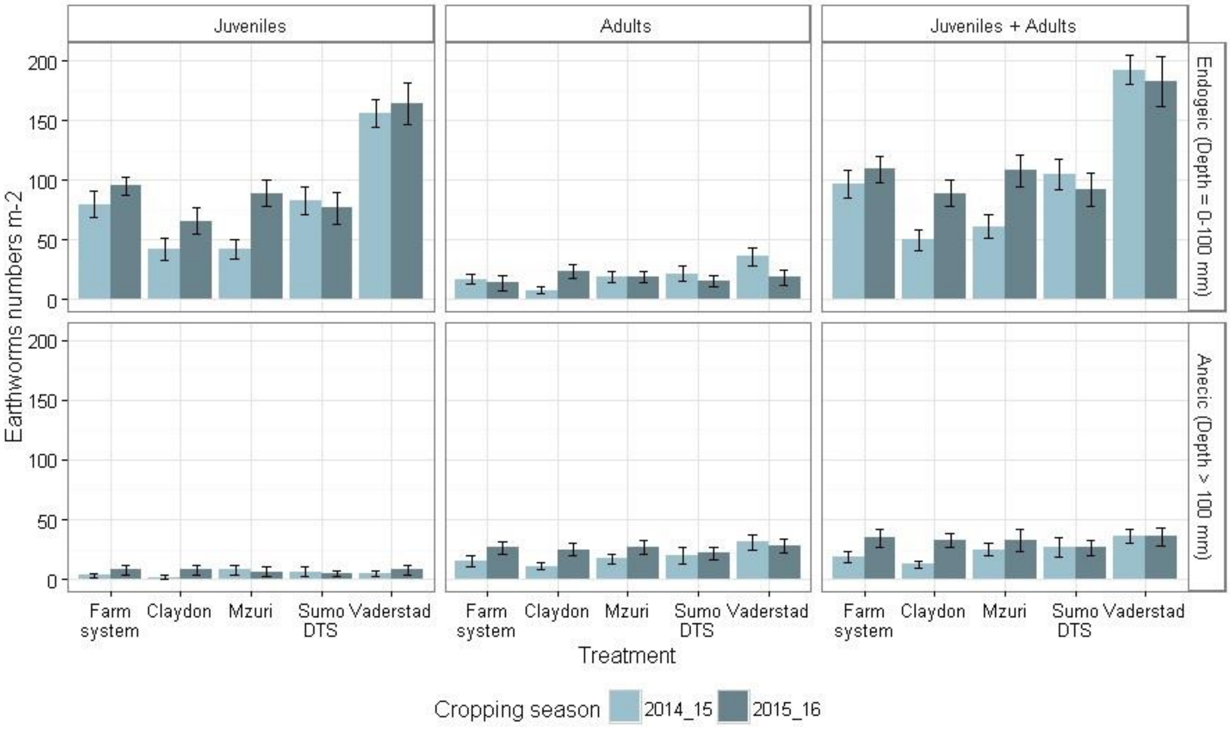


Figure 5.7. Mean earthworms numbers per meter square as separated by level of maturity and ecotypes in Snagsborough

Total numbers of earthworms, namely those found in both ecotypes which included both juveniles and adults, were also monitored. In the same field and year, the Väderstad had the significant greatest total number of earthworms (228 m$^{-2}$), compared to all other treatments (Table 5.15). Claydon was associated with a lower value (63 m$^{-2}$) than the Farm system and Sumo DTS (116 and 131 m$^{-2}$ respectively). The Mzuri value (87 m$^{-2}$) was not statistically different from that of the Farm system. In Top Furze earthworms were assessed within the three cropping seasons. In 2013-14 there was no treatment effect on the anecic earthworms in all levels of maturity. However, the Farm system had lower ($p<0.05$) number of juveniles (64 m$^{-2}$) and juveniles plus adults (75 m$^{-2}$) than the Väderstad and Mzuri (126 and 152 m$^{-2}$) for the endogeic ecotype (Figure 5.8). Regarding the second year, the ANOVA similarly didn't result in any significant treatment effect on the anecic earthworms across all levels of maturity (Figure 5.8).

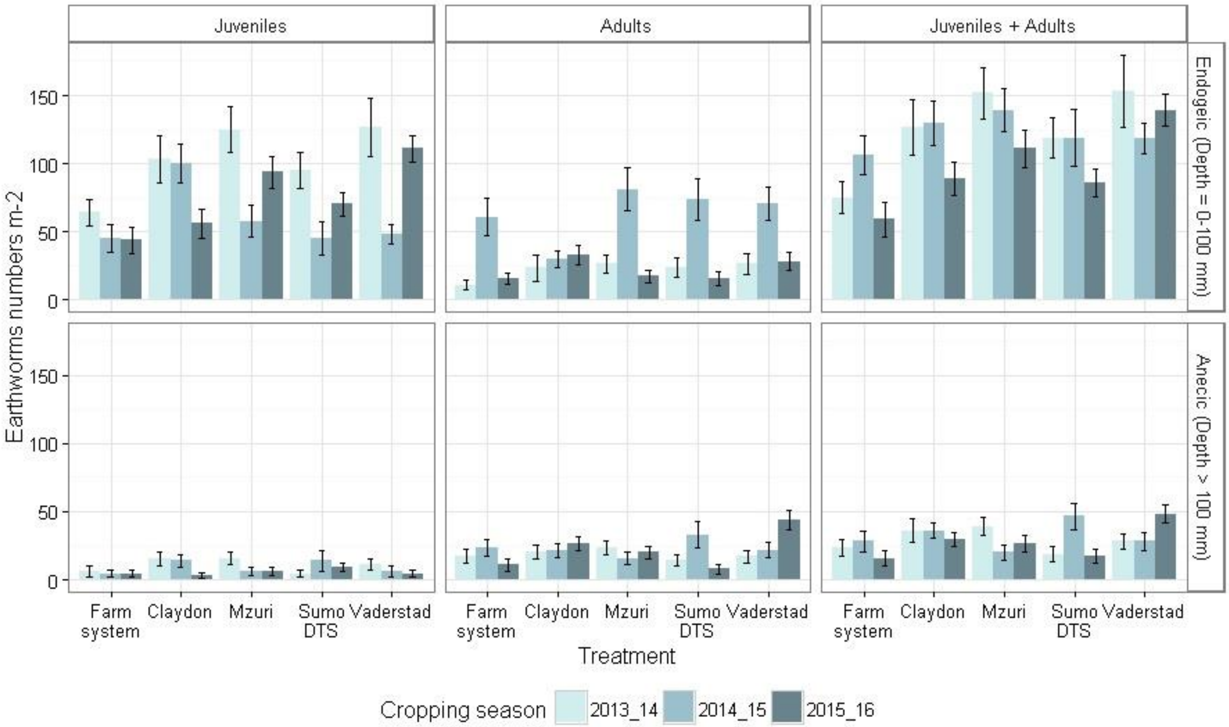


Figure 5.8. Mean earthworms numbers per meter square as separated by level of maturity and ecotypes in Top Furze

On the other hand, in 2014-15 the Claydon had a higher number ($p<0.05$; 100 m$^{-2}$) of endogeic juveniles than the other treatments (range: 46-58 m$^{-2}$). Endogeic adults, by contrast, were observed to be significantly lower in Claydon (30 m$^{-2}$) than the Mzuri, Sumo DTS and Väderstad (81, 73, 70 m$^{-2}$). Within last year, the anecic number of juveniles were not different among treatments ($p>0.05$). However, the ANOVA of adults and adults + juveniles numbers showed that the Väderstad treatment resulted in greater numbers (44 and 49 m$^{-2}$) than the rest of the treatments. The statistically decreasing order after Väderstad was, in both cases, Claydon, Mzuri, Sumo DTS and Farm system. For the adults the later treatments didn't differ statistically (range: 16-30 m$^{-2}$) but for the adults plus juveniles, the Farm system and Sumo DTS were significantly lower (8 and 11 m$^{-2}$) than the Claydon (27 m$^{-2}$). Finally in terms of the endogeic earthworms, there was a treatment effect ($p<0.05$) on juveniles and juveniles plus adults. In both cases, Väderstad (111 and 139 m$^{-2}$) and Mzuri (94 and 111 m$^{-2}$) had significant ($p<0.05$) greater values than the Farm system (44 and 60 m$^{-2}$). The Claydon, Sumo DTS and Farm system had statistically similar values in both circumstances (range for juveniles: 44-71 m$^{-2}$; range for juveniles plus adults: 60-90 m$^{-2}$).

Table 5.15. Summary of the grand total number of earthworms (m$^{-2}$) per year for both fields

| Treatment | Snagsborough | | Top Furze | | |
|---|---|---|---|---|---|
| | 2014-15 | 2015-16 | 2013-14 | 2014-15 | 2015-16 |
| Farm system | 116 bc | 144 b | 98 b | 134 a | 75 c |
| Claydon | 62 d | 122 b | 162 a | 166 a | 119 b |
| Mzuri | 88 cd | 141 b | 191 a | 159 a | 137 b |
| Sumo DTS | 131 b | 119 b | 137 ab | 166 a | 103 bc |
| Väderstad | 228 a | 219 a | 181 a | 147 a | 187 a |
| Mean | 158 | 149 | 154 | 154 | 124 |

*Means with the same letter are not significantly different and apply to columns; Väderstad was replaced by Horsch in 2014-15 in Top Furze & 2015-16 in Snagsborough

In summary in both years that earthworms were monitored in Snagsborough, the grand total numbers of Väderstad were significantly higher than the others treatments (Table 5.15). In Top Furze, in 2013-14 the Farm system gave significant lower earthworm numbers (98 m$^{-2}$) than the Claydon, Väderstad and Mzuri (162, 181 and 191 m$^{-2}$ respectively). The Sumo DTS value was similar to all other treatments. Likewise in 2015-16 the Väderstad value (187 m$^{-2}$) was greater than the Mzuri (137 m$^{-2}$), Claydon (119 m$^{-2}$) and Farm system (75 m$^{-2}$), with the latter having statistically similar earthworm abundance as compared to the Farm system but significant lower than all the other treatments (Table 5.15). In 2014-15 there was no treatment effect on grand total number of earthworms ($p>0.05$). In general, the majority of earthworms were endogeic, namely they were apparent at the top layer of soil (0-100 mm), and they were significant higher in numbers than the anecic (Table 5.15).

The juveniles were more abundant than adults at 0-100 mm and the opposite occurred at depths greater than 100 mm (Figure 5.7; Figure 5.8). Earthworms' biomass was also monitored for the same years in both fields. In 2014-15 in Snagsborough, their biomass in the Väderstad plots (126 g m$^{-2}$) was significant greater than in the Claydon, Mzuri and Farm system plots (33, 46 and 63 g m$^{-2}$ respectively). The Sumo DTS gave significant higher value (94 g m$^{-2}$) than the Mzuri and Claydon but similar statistically to Väderstad and Farm system. Finally in the last season (2015-16), the Väderstad gave higher weight of earthworms (73 g m$^{-2}$) than the Claydon (44 g m$^{-2}$), Farm system (41 g m$^{-2}$) and Sumo DTS (36 g m$^{-2}$) but similar to Mzuri (49 g m$^{-2}$) (Table 5.16).

Table 5.16. Mean values of earthworms' biomass (g $m^{-2}$) per year for both fields

| Treatment | Snagsborough | | Top Furze | | |
|---|---|---|---|---|---|
| | 2014-15 | 2015-16 | 2013-14 | 2014-15 | 2015-16 |
| Farm system | 63 bc | 41 b | 13 d | 86 ab | 14 b |
| Claydon | 33 c | 44 b | 35 bc | 49 b | 77 a |
| Mzuri | 46 c | 49 ab | 57 a | 105 a | 27 b |
| Sumo DTS | 94 ab | 36 b | 26 cd | 113 a | 20 b |
| Väderstad | 126 a | 73 a | 51 ab | 109 a | 100 a |
| Mean | 72 | 49 | 48 | 92 | 48 |

*Means with the same letter are not significantly different and apply to columns; Väderstad was replaced by Horsch in 2014-15 in Top Furze & 2015-16 in Snagsborough

Finally in 2013-14 earthworms in Top Furze weighed significant more per metre square in the Mzuri treatment (57 g $m^{-2}$) than the Claydon, Sumo DTS and Farm system (35, 26 and 13 g $m^{-2}$). In 2014-2015, the lowest value (48 g $m^{-2}$) occurred in the Claydon treatment while in the last year, Väderstad and Claydon had a higher earthworm biomass (100 and 77 g $m^{-2}$) than the Mzuri, Sumo DTS and Farm system (14-27 g $m^{-2}$) (Table 5.16). The changes between cropping seasons in earthworm numbers were assessed carrying out an analysis of variance, in terms of the significance of the difference obtained when subtracting the earthworms numbers among pairs of cropping seasons. The results showed no significant treatment effect ($p>0.05$) on change in earthworm numbers within all ecotypes in Snagsborough. On the other hand, significant changes were found between years in Top Furze (Table 5.17).

Between year 2 and 3, the Väderstad gave a higher significant positive change (+41 $m^{-2}$) than all other treatments. There was a significant ($p<0.05$) change of the earthworms that dwell deeper than 100 mm (anecic). Väderstad showed a greater increase (+20 $m^{-2}$) than the Claydon, Farm system and Sumo DTS (-6, -12 and -30 $m^{-2}$). Mzuri increased the deep earthworms numbers as well (+6 $m^{-2}$), which was not statistically different to Claydon and Farm system but it did differ significantly to that of Sumo DTS. Finally, between year 1 and 2 Sumo DTS increased the deep earthworms (+28 $m^{-2}$) more than the Väderstad, Claydon (no change between years) and Mzuri which showed a decrease by 19 $m^{-2}$.

Table 5.17. Analysis of variance of the difference in earthworm numbers m$^{-2}$ over cropping seasons', separated by ecotypes in Top Furze.

| Treatment | Difference | Difference | |
|---|---|---|---|
| | Year 1-2 | Year 2-3 | |
| | Anecic | Anecic | Grand total |
| Farm system | +5 ab | -12 bc | -59 b |
| Claydon | 0 b | -6 b | -47 b |
| Mzuri | -19 b | +6 ab | -22 b |
| Sumo DTS | +28 a | -30 c | -62 b |
| Väderstad | 0 b | +20 a | +41 a |

*Means with the same letter are not significantly different and apply to columns
Väderstad was replaced by Horsch in Sept 2014 (Year 2)

### 5.3.7 Available nitrogen for plant uptake

The analysis of variance showed that $NH_4^+$ did not vary ($p>0.05$) among treatments. Its value ranged from 0 to 0.5 mg $NH_4^+$ per kilogram of soil. The general trend was that $NH_4^+$ declined over time in all the treatments. In Snagsborough, treatment differences in $NO_3^-$ were also not significant ($p>0.05$) for all cropping seasons, with values ranging from 11 to 37 mg per kilogram of soil. However, the pairwise comparisons did reveal that in year 1 ($p=0.1$) Mzuri had greater amount of nitrate (24 mg kg$^{-1}$ soil) than the Claydon and Farm system (12 mg kg$^{-1}$ soil). In year 3 ANOVA did not show any significant effect ($p=0.3$), but the comparisons showed higher nitrates for Claydon (47 mg kg$^{-1}$ soil) compared to Väderstad (31 mg kg$^{-1}$ soil) (Table 5.18).

Table 5.18. Soil nitrate (mg kg$^{-1}$ soil) for all cropping seasons and both fields

| Treatment | 2013-14 | | 2014-15 | | 2015-16 | |
|---|---|---|---|---|---|---|
| | SN | TF | SN | TF | SN | TF |
| Farm system | 12 b | 16 a | 25 a | 35 a | 32 ab | 6 ab |
| Claydon | 12 b | 27 a | 15 a | 35 a | 47 a | 7 a |
| Mzuri | 24 a | 23 a | 23 a | 23 ab | 34 ab | 5 ab |
| Sumo DTS | 14 ab | 22 a | 18 a | 16 b | 38 ab | 6 ab |
| Väderstad | 18 ab | 15 a | 21 a | 29 ab | 31 b | 4 b |
| Mean | 16 | 21 | 20 | 28 | 36 | 6 |

*Means with the same letter are not significantly different and apply to columns; SN: Snagsborough; TF: Top Furze;
Väderstad was replaced by Horsch in 2014-15 in Top Furze & 2015-16 in Snagsborough

In Top Furze in year 2 there was a significant treatment effect on soil nitrate ($p=0.03$). The Claydon and Farm system had higher values (35 mg kg$^{-1}$ soil) than the Sumo DTS (16 mg kg$^{-1}$ soil) (Table 5.18). In last year the pattern followed was similar, but values for nitrate were lower than year 2.

### 5.3.8 Water stable aggregates

There was no significant treatment effect on the level of water stable aggregates in 2013-14 and 2014-15 (p>0.05) for both fields. However in Snagsborough in 2015-16, the level of water stable aggregates in the Väderstad treatment (29.8%) was higher than the other treatments, which had similar values of 22.7-25.3% (Figure 5.9). A similar response was observed in Top Furze in the pairwise comparisons, but the ANOVA resulted in a p value of p=0.10. It worth also noting that, even though not significant, the highest values in both fields were held by Väderstad (Table 5.19).

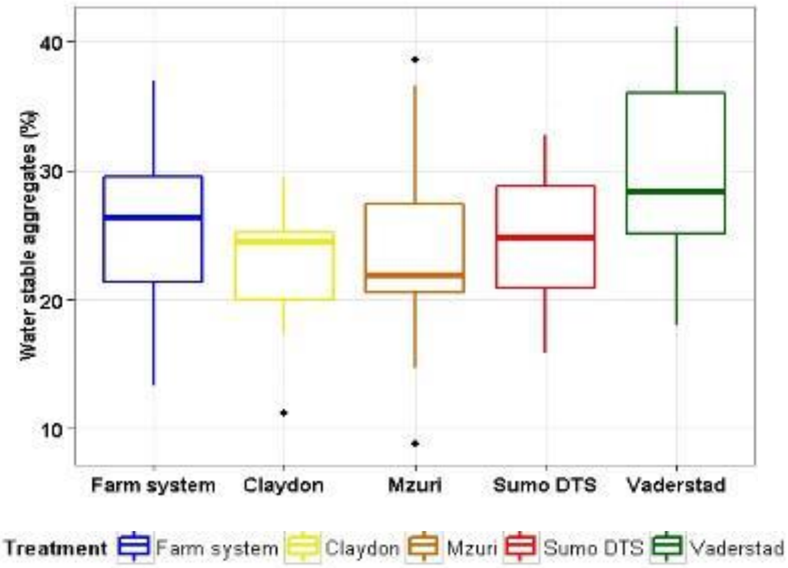


Figure 5.9. Water stable aggregates (%) in Snagsborough in 2015-16. Boxplot shows the spread of the data set (box = 25-75% of the data, line within box = median value, upper whisker = upper 25% of the data, lower whisker = lower 25% of the data) (n = 80).

Table 5.19. Mean water stable aggregates values (%) per cropping season and field

| Treatment | 2013-14 | | 2014-15 | | 2015-16 | |
|---|---|---|---|---|---|---|
| | SN | TF | SN | TF | SN | TF |
| Farm system | 24.3 a | 39.9 a | 27.3 a | 42.4 a | 25.3 b | 43.3 b |
| Claydon | 22.7 a | 39.5 a | 25.8 a | 41.0 a | 22.7 b | 43.6 b |
| Mzuri | 24.7 a | 34.3 a | 29.9 a | 38.9 a | 23.8 b | 44.2 b |
| Sumo DTS | 25.1 a | 39.3 a | 25.9 a | 42. a | 24.9 b | 44.3 b |
| Väderstad | 25.5 a | 40.6 a | 33.2 a | 43.1 a | 29.8 a | 51.0 a |
| Mean | 24.4 | 38.7 | 28.4 | 41.5 | 25.3 | 45.3 |

*Means with the same letter are not significantly different and apply to columns; SN: Snagsborough; TF: Top Furze; Väderstad was replaced by Horsch in 2014-15 in Top Furze & 2015-16 in Snagsborough

Analysis of variance was also carried out comparing the WSA % between pairs of cropping seasons. The results showed no significant change between treatments over time.

### 5.3.9 Soil hydraulic conductivity

The soil hydraulic conductivity was measured in 2014-15 for both fields and the results showed no significant treatment effect in Snagsborough ($p=0.07$) and Top Furze ($p=0.35$). However the pairwise comparisons in Snagsborough did reveal that Väderstad value of $6.86 \times 10^{-5}$ cm $s^{-1}$ was higher than that of Mzuri, Farm system, Sumo DTS ($3.53 \times 10^{-5}$, $3.62 \times 10^{-5}$, $4.09 \times 10^{-5}$ respectively) but similar to Claydon ($5.28 \times 10^{-5}$ cm $s^{-1}$) (Table 5.20).

Table 5.20. Soil hydraulic conductivity (cm $s^{-1}$) as monitored in both fields in 2014-15

| Treatment | 2014-15 | |
|---|---|---|
| | SN | TF |
| Farm system | $3.62 \times 10^{-5}$ b | $1.27 \times 10^{-4}$ a |
| Claydon | $5.28 \times 10^{-5}$ ab | $6.00 \times 10^{-5}$ a |
| Mzuri | $3.53 \times 10^{-5}$ b | $1.24 \times 10^{-4}$ a |
| Sumo DTS | $4.09 \times 10^{-5}$ b | $1.63 \times 10^{-4}$ a |
| Väderstad | $6.86 \times 10^{-5}$ a | $1.18 \times 10^{-4}$ a |
| Mean | 28.43 | 41.48 |

*Means with the same letter are not significantly different and apply to columns; SN: Snagsborough; TF: Top Furze; Väderstad was replaced by Horsch in Top Furze

## 5.4 Discussion

### 5.4.1 Immediate effect of tillage treatment on bulk density

The change in soil bulk density over time was examined for each field. In October 2014, immediately after the imposition of tillage treatments in Snagsborough when the field was planted to wheat, the soil bulk density (0-50 cm) within the Farm system (1.169 Mg $m^{-3}$) was less than that in the other four systems (1.284-1.339 Mg $m^{-3}$) (Table 5.2). The two pass Farm system for wheat is the most intensive of the tillage systems investigated. Hence it should be expected that the higher intensity of tillage, results in a lower soil bulk density immediately after tillage. A similar response was observed in Top Furze at the same depth where the Farm system had the lowest bulk density immediately after tillage (Table 5.3). Hence it is apparent that relatively more-intense two pass tillage system led to a reduction in soil bulk density at the surface layer immediately after tillage. This is in line with Jabro et al. (2016) who concluded that high intensity tillage results in lower bulk density than no tillage systems at 0-400 mm.

### 5.4.2 Medium-term effect of tillage treatment on bulk density

Although the Farm system for wheat reduced the soil bulk density immediately after tillage, by the end of the cropping season the benefits of the tillage on soil bulk density were no longer apparent. In fact in August 2015, the soil bulk densities, at both depths, in Snagsborough showed no significant treatment effect. Väderstad was associated with the lower, but not significantly different, values (1.161 at 0-50 mm and 1.302 Mg $m^{-3}$ at 150-200 mm). In August 2015 in Top Furze the soil bulk density (0-50 mm) of the Sumo DTS (1.157 Mg $m^{-3}$) was only lower than that of the Farm system (1.248 Mg $m^{-3}$) but statistically similar to the others.

Hence it appears that the benefits in lowering soil bulk density immediately after tillage are not maintained to the end of the cropping season. These results agree with the findings of Da Veiga et al. (2008) study, where it is underlined that any change in soil bulk density immediately after tillage is diminished over time due to natural soil reconsolidation.

### 5.4.3 Soil bulk density at 150-200 mm

There was no obvious consistent effect of the different tillage systems on the soil bulk density at 150-200 mm. The Väderstad showed a smaller increase in bulk density at depth following tillage than the Mzuri and the Sumo DTS in 2014, and the Farm system significantly decreased the bulk density at depth compared to the Mzuri and the Väderstad system in 2015 (Table 5.2). Similarly in Top Furze after tillage in October 2015, the bulk density beneath the Väderstad treatment was significantly lower than that for the Mzuri (Table 5.3). The lower bulk density with the Väderstad compared to Mzuri in year 3, could perhaps provide some evidence of reduced cultivation leading to lower bulk densities at depth in the long term. Chaplain et al. (2010) reported that no tillage can have contrasted effects on soil bulk density whereas the study carried out by Huang et al. (2015) reported that low disturbance tillage systems (no-tillage) decreased (even not significant) the soil bulk density to a greater extent than conventional tillage at 0-200 mm.

### 5.4.4 Penetration resistance

In 2015 in Snagsborough at 150-200 mm, the Claydon showed a greater increase in the penetration resistance than the Farm system and the Sumo DTS. This can be related to the working depth and geometry of the main working implement of the Claydon. As described in Chapter 4, the Claydon had a straight 70° rake angle tine and worked slightly below critical depth (Section 4.1) causing the soil to fail laterally at depth. This could explain how the Claydon treatment increased penetration resistance at depth (Table 5.4).

Likewise between September and October 2014 the Sumo DTS at the same depth led to an increase in penetration resistance (+0.412 MPa) whilst the Farm system decreased it (-0.171 MPa). This could be explained by Sumo DTS tine's geometry which was a straight non-winged tine, working deep and possibly below critical depth. However, as mentioned in Chapter 4 Sumo DTS was not supplied by the manufacturer for the controlled experiments in Cranfield's soil bin facility. These results match those observed in earlier studies which indicate lateral failure at depth for straight non-winged deep working tines (He et al. 2016; Godwin 2007; Spoor & Godwin 1978). As mentioned in the Literature Review (Chapter 2), there is evidence of a negative relationship between soil moisture content and penetration resistance. In year 2 and 3 at 150-200 mm depth in Top Furze, the Farm system had a high moisture content (32%) after tillage (Table 5.8) and a low penetration resistance (Table 5.5).

### 5.4.5 Change in soil carbon

Based on the literature, measurable changes in soil organic carbon in agricultural soils usually require several years and hence significant changes in organic carbon within a particular cropping season are difficult to detect. However, in Top Furze, Väderstad and Mzuri significantly increased the total soil organic carbon by more than the Sumo DTS and Farm system at 0-50 mm within a time span of 3 years (Table 5.10). This could be related to the amount of the crop residue left on the soil surface after tillage which was significantly higher for the Väderstad and Mzuri than the Farm system and Sumo DTS in the same field and year (Chapter 6).

When the surface soil carbon was compared in Top Furze between year 1 and 3, the lowest increase in soil carbon occurred in the Farm system (Table 5.10). This is associated with the two-pass system which disturbed the soil surface more than the one pass treatments. On the other hand, the 150-200 mm soil layer could only be reached mechanically by the working leg of the first pass treatment of the Farm system (Sumo Trio), which transferred organic material from the surface to the 150-200 mm depth, increasing the soil carbon stock at that depth during the last year (but not significantly).

Väderstad and Mzuri were the only treatments to increase soil carbon stocks in Top Furze over three years (+1.113 and +0.487 t C ha$^{-1}$). That increase was significantly higher than the Farm system which reduced the carbon stocks at 0-50 mm by 2.452 t C ha$^{-1}$. However the above values were dependent on the treatments' mean bulk density. Assuming a fixed soil bulk density value of 1.4 Mg m$^{-3}$, an increase of around 0.4% in total organic carbon, observed by Mzuri and Väderstad (Table 5.10), would result in an addition of 2.8 t C $ha^{-1}$ at the top 50 mm of soil.

Changes in soil carbon in the surface layer, as mentioned in the literature review (Chapter 2), can occur by increasing the organic material left on soil surface after harvest as crop residue. A linear regression analysis (Equation 5.2) showed a positive significant effect of crop residue on total organic carbon (*TOC*) ($R^2 = 0.10$; n = 80; $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$)).

$$TOC = 0.004\ (\pm\ 0.002)\ ^{**}\ \text{Crop residue} + 2.6\ (\pm\ 0.1)\ ^{***} \qquad \text{Eq. (5.2)}$$

Equation 5.2 suggests that for every 10% increase in crop residue left on the soil surface, the total soil organic carbon is increased by 0.04%, equivalent to an increase of 0.28 t C $ha^{-1}$ within a timespan of three years in the top 50 mm given a soil bulk density of 1.4 Mg $m^{-3}$. A more detailed analysis of the crop residue retained on the soil surface and how each treatment affected it, is presented in Chapter 6.

### 5.4.6 Relationship between soil organic carbon and bulk density

The relationship between total soil organic carbon and soil bulk density was initially assessed by producing a scatter plot and a regression analysis. The scatter plot (Figure 5.10) suggests a negative relationship between the total soil organic carbon and soil bulk density. A regression analysis (Equation 5.3) for the 0-50 mm data in Top Furze (n = 80; $R^2 = 0.10$; $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$) indicated that the higher the amount of total soil organic carbon (*TOC*), the lower the soil bulk density (Figure 5.11). This equation suggests that for every 1 % increase in total soil organic carbon, soil bulk density is to decrease by 0.1 Mg $m^{-3}$ (Equation 5.3). Such a decrease will facilitate plant roots elongation by creating more voids in a particular volume of soil, which can prove highly beneficial especially in poor aerated soil conditions.

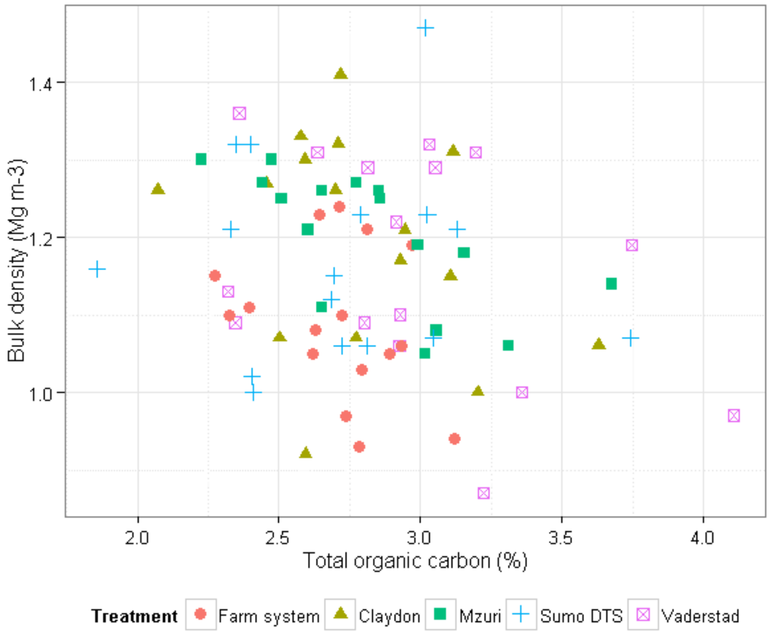


Figure 5.10. Scatter plot of the soil bulk density and total soil organic carbon at 0-50 mm for Top Furze in 2015-16

$$\textit{Bulk density} = -0.10\ (\pm 0.03)\ ^{**}\ \textit{TOC} + 1.4\ (\pm 0.1)\ ^{***} \qquad \text{(Eq 5.2)}$$

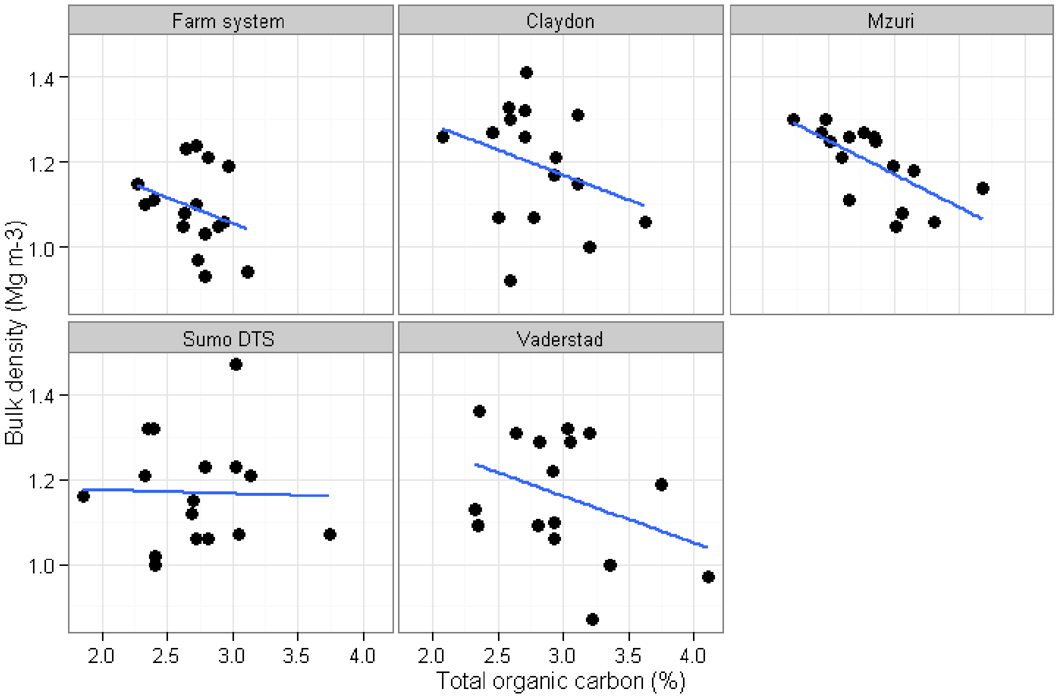


Figure 5.11. Regression analysis between bulk density and total organic carbon in Top Furze at 0-50 mm

### 5.4.7 Soil microbial biomass carbon

A significant treatment effect was observed in year 1 in Top Furze with Väderstad having greater microbial biomass carbon than the Claydon and Farm system. Likewise, in all years and both fields the Väderstad treatment had the highest value (even though it was not significant). This is consistent with Titi (2003) and Kabiri et al. (2016) who found that no tillage and less disturbed soils retain more crop residues, and hence, sufficient substrate to sustain microbial community in higher levels than more intensive tillage systems.

The linear regression analysis carried out for both fields and seasons, showed that there was no significant correlation between microbial biomass carbon and total organic carbon for all five treatments, in all years and both fields ($r^2$ ranged from 0.0003 to 0.24). Changes in Cmic:Corg ratio within agricultural soils are difficult to occur and usually such changes take effect in the long term (Zuber and Villamil, 2016).

### 5.4.8 Earthworms

In the majority of cases the Väderstad resulted in a significantly higher number of earthworms in both fields compared to other treatments (Table 5.15). Between year 1 and 2 in Top Furze, an increase in earthworms in the Farm system can be attributed to the Farm system comprising only a single pass when oilseed rape is established, compared to years 1 and 3 when a two pass system was applied to establish the wheat crop. Hence in year 3 in Top Furze, the Farm system led to reduced earthworm numbers (Table 5.17). It appears that greater soil disturbance as well as double number of passes will result in a decline in earthworm abundance.

In terms of earthworm biomass the shallow (endogeic) earthworms were more numerous and weighed more than the anecic species. Väderstad resulted in greater values of earthworm biomass in both fields. The Farm system, as with earthworm numbers, increased earthworm biomass in the second season, when oilseed rape (one pass system) was planted in Top Furze. In summary, the majority of earthworms across the whole experiment were juveniles and red-green in color. The anecic were fewer in number, but weighed more per individual and were predominantly adults. The length for the juveniles ranged from 3 to 6 cm although some adults were as long as 15 cm. The main taxonomy classes were *Octolasion cyaneum, Lumbricus terrestris* and *Allolobophora chlorotica.* One explanation (as mentioned in Chapter 2) of why earthworm populations increased is that: the abundance of soil biology and earthworms in particular depends on organic material left on the soil surface, including crop residue. The linear regression supported this, with a significant positive relationship between crop residue and earthworm abundance (Figure 5.12). The analysis in Snagsborough (n = 80; $R^2$ = 0.10; `*p<0.1; **p<0.05; ***p<0.01`) indicated that the higher the amount of crop residue left on soil surface, the higher the earthworms numbers (Equation 5.3). This equation suggests that for every 10 % increase in crop residue left on the soil surface, there will be 1,200 more earthworms per hectare.

$$\text{Earthworms numbers} = 1.2\ (\pm 0.4)\ {}^{***}\ \text{Crop residue} + 63.5\ (\pm 20.2)\ {}^{***} \qquad \text{Eq. (5.3)}$$

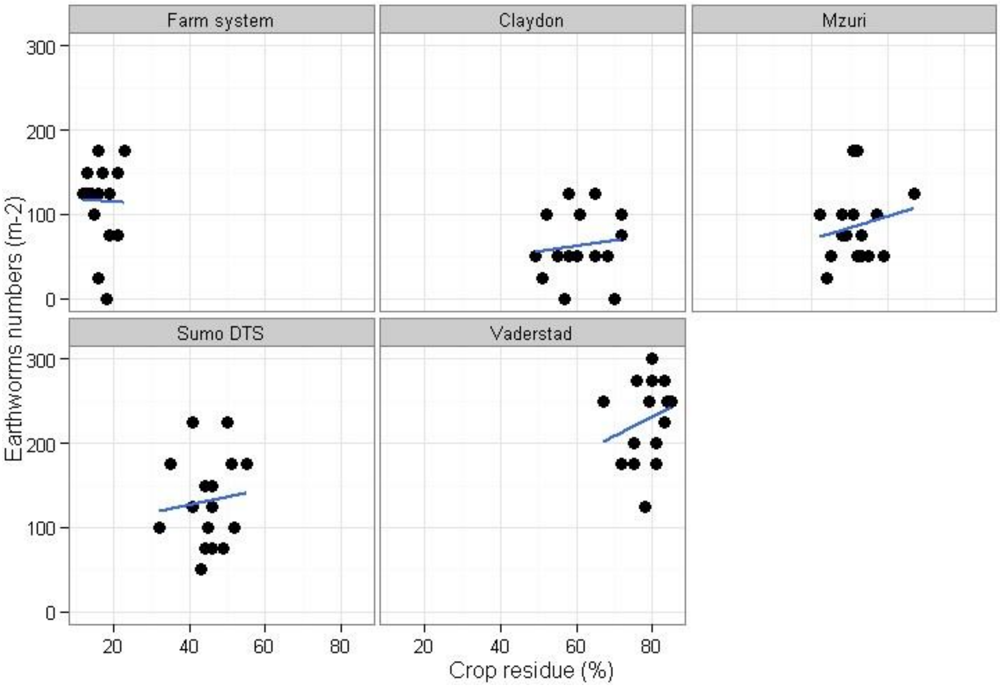


Figure 5.12. Linear regression analysis between crop residue and total numbers of earthworms in Snagsborough in 2014-15

### 5.4.9 Available nitrogen for plant uptake

In terms of ammonium ($NH_4^+$), the analysis showed no treatment effect during the experiment. In general the nitrate ($NO_3^-$) levels in both fields increased over time, although in Top Furze in year 3 (when planted to wheat), values dropped to 4-5 mg $kg^{-1}$ (Table 5.18). The low nitrogen values in Top Furze within last year, are explained by the fact that the field was sampled in spring 2016 before the application of nitrogen fertilizer by the farmer.

There were higher levels of $NO_3^-$, compared to $NH_4^+$, at the field site. The first possible reason for this is the high clay content of the soils. Ammonium's positive charge makes it fix easily to clay soil particles or organic matter. This turns nitrate into a more available form of nitrogen to plants than $NH_4^+$ in clayey soils. Secondly there was a trend (not significant) that total organic carbon was increasing during the experiment. Organic matter with its negative charge can attract $NH_4^+$ in a greater degree than $NO_3^-$. Thirdly higher levels of organic matter in soil can mean more food for soil microorganisms. Available food for microorganisms can lead to mineralization and immobilization of $NO_3^-$ and $NH_4^+$ (locking them up in biomass) making both forms unavailable to plants. However, immobilization only temporarily locks up nitrogen. When the microorganisms die, the organic nitrogen contained in their cells is converted back by mineralization and nitrification to plant available forms. An extended review carried out by Nieder et al. (2011) on fixation and de-fixation of $NH_4^+$ in soils, also supports the above, by indicating that some soils (2:1 clay minerals) are able to bind $NH_4^+$ in such a manner that these cannot be easily replaced by other cations and released back into the soil solution.

### 5.4.10 Water stable aggregates and hydraulic conductivity

Väderstad possessed the highest proportion of water stable aggregates in both fields, but this effect was not statistically significant, except ($p<0.05$) in Snagsborough in year 3. As a general note the soil in Top Furze (clay) had a greater proportion of water stable aggregates than the clay loam in Snagsborough in all years. As mentioned in section 2.4.3 soil organic carbon acts as a binding agent and as a nucleus in the formation of aggregates with clay content and soil biology playing an important role as well. However the linear regression could not detect any relation between earthworms and water stable aggregates.

Nonetheless, a significant positive relationship between water stable aggregates and total organic carbon was observed in the linear regression (Figure 5.13). The analysis in Top Furze (n = 80; $R^2 = 0.10$; $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$) indicated that the higher the amount of soil total organic carbon, the higher the proportion of water stable aggregates (Equation 5.4). Equation 5.4 suggests that a 1% increase in soil total organic carbon (over the range tested) will result in a 15% increase in water stable aggregates.

$$\text{Water stable aggregates} = 14.9\ (\pm 3.2)^{***}\ \text{TOC} + 3.4\ (\pm 9.2) \qquad \text{Eq. (5.4)}$$

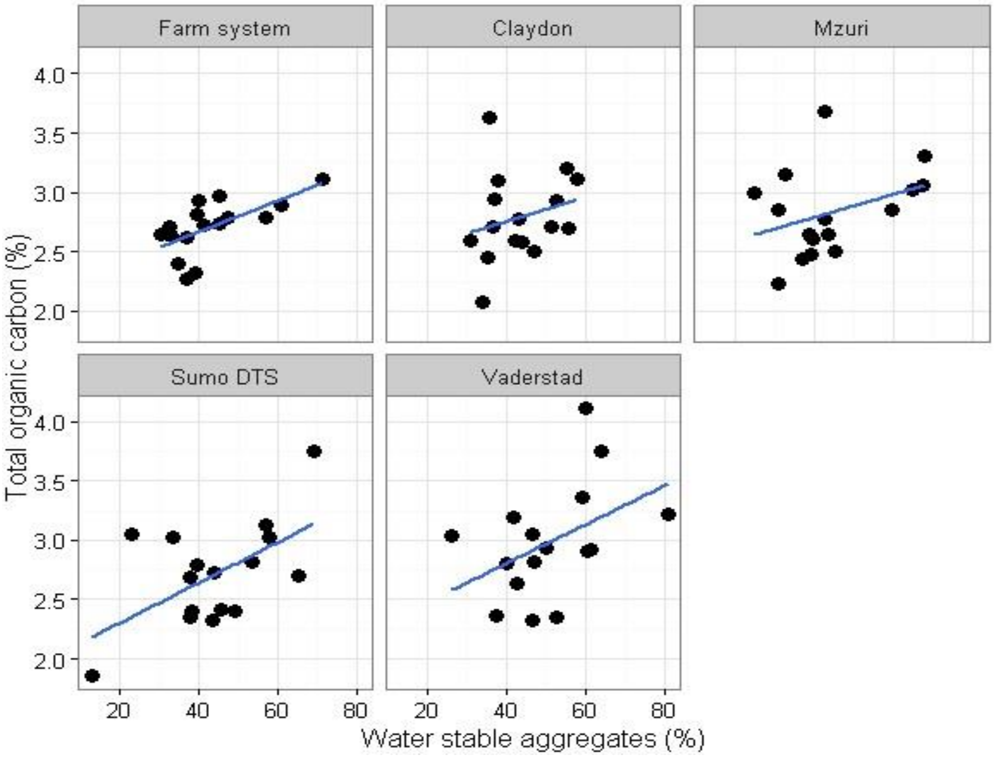


Figure 5.13 Linear regression analysis between total organic carbon and water stable aggregates in Top Furze in 2015-16

In summary, treatments that tend to increase surface crop residue after tillage operation are more likely to increase total organic carbon in the long term. This in turn means food for soil organisms like earthworms, increasing their numbers. The increase of soil carbon among other benefits can also act as a glue - binding agent which in turn will increase the percentage of water stable aggregates in soil.

The analysis of variance did not show any significant effect on hydraulic conductivity in 2014-15. Values in Snagsborough (p=0.07) were higher for Väderstad than for Mzuri, Farm system and Sumo DTS. Data from several sources have associated increased water stable aggregates and hydraulic conductivity with reduced tillage intensity (Abid & Lal 2008; Sharma et al. 2011; Paul et al. 2013).

## Conclusions

- The high intensity two pass Farm system reduced soil bulk density at both 0-50 mm and 150-200 mm when measured immediately after tillage for both fields. By contrast the low intensity Väderstad tillage treatment tended to result in no reduction in surface bulk density immediately after tillage. However by the end of the cropping season the benefits of the more disruptive Farm system on soil bulk density were no longer apparent.
- Claydon in year 3 showed greater values of penetration resistance than the other treatments at 150-200 mm. The similar increase at depth was also found in Chapter 4 under the controlled condition experiments.
- At the same depth in year 2 Sumo DTS showed a greater increase in penetrometer resistance than the Farm system. This may be a result of the Sumo DTS having a similar working depth and geometry as the Claydon (Unfortunately the Sumo DTS was not tested in Chapter 4).
- All treatments tended to increase the total soil organic carbon over time. However the positive increase with the Väderstad and Mzuri at 0-50 mm was greater than with the Sumo DTS and Farm system within a time span of 3 years.
- There were significant positive relationships between total organic carbon and bulk density as well as between total organic carbon and crop residue.

- A regression analysis indicated that a 10% increase in crop residue left on the soil surface, would increase total soil organic carbon by 0.04% which is translated to an increase of 0.28 t C ha$^{-1}$ at the top 50 mm over a period of three years.
- The Väderstad resulted in a significantly greater microbial biomass than the Claydon and Farm system in year 1 and greater values (although not significant) over all years within both fields.
- All over the 3-year experiment, the Väderstad resulted in the highest number of earthworms while the Farm system reduced them in wheat drilling within year 1 and 3 (two pass system).
- There was a significant positive relationship between crop residue and earthworms abundance. Väderstad that left the greatest levels of crop residue on the soil surface resulted in the highest numbers of earthworms. A regression analysis indicated that for every 10 % increase in crop residue left on the soil surface, there will be 1,200 more earthworms per hectare.
- There was a significant treatment effect on water stable aggregates with Väderstad possessing the highest value in year 3 ($p<0.05$). However in all years within both fields the Väderstad resulted in the greatest soil aggregation (but not significant)
- There was a significant positive relationship between water stable aggregates and total organic carbon. Treatments with high percentages of organic carbon (such as Väderstad) resulted in higher values of soil aggregation.

# 6 EFFECT ON CROP PERFORMANCE

## 6.1 Introduction

This chapter presents the crop yields and associated measures of crop performance for each season (2013-14, 2014-15, and 2015-16) for both wheat and oilseed rape. As described in Chapter 2, the yield of wheat and oilseed rape can be expressed in terms of yield components (Equation 6.1).

$$\text{Yield (g m}^{-2}\text{)} = \text{Plants density (plants m}^{-2}\text{)} \times \text{Yield per plant (g plant}^{-1}\text{)} \qquad \text{Eq. (6.1)}$$

It can also be expressed in terms of incoming solar radiation ($S$; MJ m$^{-2}$), proportional light interception ($f_S$), radiation use efficiency ($\varepsilon_S$; g m$^{-2}$), and a harvest index ($HI$) (Equation 6.2)

$$\text{Yield (g m}^{-2}\text{)} = S.\, f_S.\, \varepsilon_S.\, HI \qquad \text{Eq. (6.2)}$$

This chapter focuses on a range of agronomic measurements in order to improve our understanding of how tillage treatment affects crop yield.

## 6.2 Method

The implementation of the tillage treatments is described in Chapter 2, but the key points pertinent to this chapter are briefly highlighted. The timing of the treatments is re-presented in Table 6.1. Mzuri used a company representative to drill the experimental plots, Sumo DTS used a contractor and the Väderstad, Claydon and Farm system plots were drilled by local farmers.

Table 6.1. Dates of treatment applications per cropping season

| | Snagsborough | | | Top Furze | | |
|---|---|---|---|---|---|---|
| | 2013 | 2014 | 2015 | 2013 | 2014 | 2015 |
| | Oilseed | Wheat | Oilseed | Wheat | Oilseed | Wheat |
| Farm system (Sumo trio) | 5 Sept | - | 9 Sept | - | 28 Aug | - |
| (Sumo trio + Kuhn HR) | - | 29 Sept | - | 1 Oct | - | Trio: 5 Oct<br>Kuhn: 12 Oct |
| Claydon Hybrid | 5 Sept | 29 Sept | 8 Sept | 23 Sept | 28 Aug | 13 Oct |
| Mzuri Pro Til 3 | 5 Sept | 29 Sept | 18 Sept | 23 Sept | 28 Aug | 13 Oct |
| Sumo DTS | 5 Sept | 29 Sept | 18 Sept | 23 Sept | 28 Aug | 23 Oct |
| Väderstad Rapid | - | 29 Sept | - | 1 Oct | - | 15 Oct |
| Väderstad Seed Hawk | 5 Sept | - | - | - | - | - |
| Horsch Sprinter ST | - | - | 8 Sept | - | 28 Aug | - |

As explained in Chapter 2, delayed drilling can lead to lower canopy cover and lower yields compared to crops that have been drilled at an optimum time. The timing of the imposition of the tillage treatments was generally consistent. However there was a delay in the use of the Mzuri and the Sumo DTS treatment with the oilseed rape in autumn 2015 in Snagborough. In Top Furze, there was a delay in the Farm system and the Väderstad Rapid in September/October 2013, and a delay with the Sumo DTS in October 2015.

### 6.2.1 Crop residue

The proportion of the ground covered with crop residue after tillage was recorded on 19 September (Top Furze) and 9 October (Snagsborough) in 2014, and on 23 September (Top Furze) and 2 October (Snagsborough) in 2015. Crop residue left on soil surface is expected to differ between tillage treatments due to their intensity, soil disturbance and number of passes.

### 6.2.2 Plant density

In each season and each field, the seed rate of the oilseed rape was maintained at 50 seeds m$^{-2}$ (Table 6.2). The seed rate for the wheat was increased from 300 seeds m$^{-2}$ in 2013 and 2014 to 375 seeds m$^{-2}$ in 2015. Differences in plants density between tillage treatments may occur because of negative soil effects that can hinder establishment and crop growth. This may be reduction in pore size distribution which can reduce root growth or reductions in soil biology which can reduce organic matter decomposition which can in turn affect soil fertility and crop nutrition. Last's year seed rate for wheat was increased in an attempt to combat blackgrass infestation.

Table 6.2. Seed rates (seeds m$^{-2}$) and varieties for each crop in each cropping season

| Crop | 2013-14 | | 2014-15 | | 2015-16 | |
|---|---|---|---|---|---|---|
| | Seed rate | Variety | Seed rate | Variety | Seed rate | Variety |
| Wheat | 300 | Relay | 300 | Leeds | 375 | Reflection |
| Oilseed rape | 50 | Rhino | 50 | Harper | 50 | Extrovert |

Plant counts were carried out using a 1 $m^2$ quadrat within each plot, taking care to avoid measurements near to the plots' borders and visible traffic lanes. It is worth mentioning that the row space of the Farm system was 500 mm, Väderstad row space was 125 mm and Mzuri, Claydon and Sumo had a row space of 330, 300 and 330 mm respectively. Finally all the amount chemical applications were the same for all treatments and their detailed description for all years and both fields is presented in Appendix C. These included fertilisers, herbicides, insecticides and fungicides.

### *6.2.3* Normalized Difference Vegetation Index (NDVI)

The NDVI was measured using the Crop Circle ACS-470 Multi-spectral crop canopy device, mounted on a quadbike (Chapter 3; section 3.7.6). The measurements were carried out post drilling on various dates within the cropping seasons (Table 6.3).

Table 6.3. Dates of NDVI measurements

| | Top Furze | Snagsborough |
|---|---|---|
| 2013-14 | 4-Apr-14 (wheat) | 4-Apr-14 (oilseed rape) |
| 2014-15 | 6-Mar-15 (oilseed rape) | 6-Mar and 29-May-15 (wheat) |
| 2015-16 | 9-Dec-15 (wheat) | 9-Dec-15 (oilseed rape) |

NDVI measurements of canopy crop cover can provide a measure of crop growth across a field. Potential differences in NDVI could be attributed to weather condition, delay drilling and changes in soil condition that restrict crop growth (Chapter 2; sections 2.1 and 2.5).

### 6.2.4 Blackgrass spatial distribution and density per unit area

Regarding blackgrass, two parameters were assessed: i) the spatial distribution of the infested areas and ii) blackgrass heads per square metre for 2013-14 and 2015-16 in Top Furze (wheat crop).

### 6.2.5 Crop yield

Crop yield was obtained from the combine harvester's measuring system-software across both fields as described in Section 3.7.1. The output were points (called for simplicity yield points) depicting the combine harvester's track. These points corresponded to the weight of the batch of grain at the particular instant and place. The width of the experimental plots was 12 m and the combine header width was 9 m. Thus, for the yield data to be collected, a clear cut was taken in the middle of each plot, avoiding the edges. The crop yield was confounded by factors such as i) yield points close to headlands, ii) yield points within blackgrass infested areas, and iii) yield points on machinery traffic paths (tramlines). The Top Furze field (clay soil) had blackgrass infested areas when drilled to wheat (2013 and 2015). In the same field, the tramlines ran diagonally, intersecting the middle of all the experimental plots, thud influencing the yield points. Blackgrass in Top Furze when drilled in the second year (2014) with oilseed rape was better controlled and showed no infested areas. Thus in Top Furze, blackgrass was not a confounding factor in 2015, but it was in 2014 and 2016.

In contrast, the Snagsborough field had minimal weed problems for either crop (wheat and oilseed rape), and its tramlines ran parallel to the direction of the plots and did not interfere with any yield points. Thus, the only confounding factor for crop yield estimation in Snagsborough was the headland areas. For the areas close to headlands, yield measurement points within a distance of 10 m from the starting or the ending point of each plot were omitted from the analysis because of their unrepresentative low yields probably due to regular farm machinery traffic causing compaction. Lastly regarding the tramlines, yield points within 1 m of any tramline were also omitted from the crop yield analysis. For clarity, hereafter “corrected yield” refers to the yield once the confounding factors have been removed, and “measured yield” refers to the obtained yield when not accounting for the confounding factors. Thus, the “measured yield” includes the “corrected yield” along with the “yield close to headlands”, and/or “yield on tramlines”, and/or “yield in blackgrass areas”. The yields are presented separately for the two fields. The analysis of variance (ANOVA) within all cropping seasons was carried out at p=0.05 level of significance and in some cases at both p=0.05 and 0.15 levels, to understand whether yield variability could be picked up with a less rigorous level of significance.

## 6.3 Results

### 6.3.1 Crop residue

In Snagsborough in 2014 (after the harvest of the oilseed rape and when drilling the wheat), Väderstad enabled a significantly greater coverage of the surface with residue (78%), than the Claydon (60%), Mzuri (52%), and Sumo DTS (45%), with the residue coverage of the two pass Farm system being only 17% (Figure 6.1). In Snagsborough in autumn 2015 (after the harvest of the wheat and when drilling the oilseed rape), the Väderstad resulted again in the significantly highest coverage of crop residue (86%), followed by the Claydon (60%), one-pass Farm system (57%), Mzuri (55%) and Sumo DTS (54%), with the latter three being similar (p = 0.05) to one another (Figure 6.1).

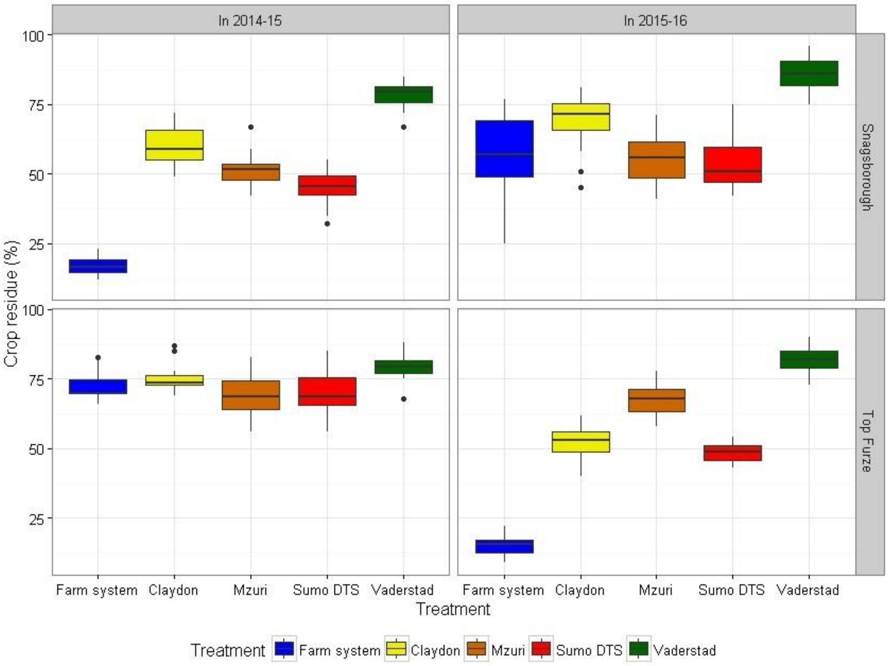


Figure 6.1. Effect of tillage treatment on the surface residue (%) for both fields in 2014-15 and 2015-16. Boxplot shows the spread of the data set (box = 25-75% of the data, line within box = median value, upper whisker = upper 25% of the data, lower whisker = lower 25% of the data).

In autumn 2014 in Top Furze (harvested wheat and drilled to oilseed rape), the coverage of crop residue with the Väderstad (79%) was significantly greater than with the one-pass Farm system (72%), the Sumo DTS (70%) and the Mzuri (68%) (Figure 6.1). The coverage with the Claydon (75%) was statistically similar to the Väderstad, but it was higher (p = 0.05) than the Mzuri (68%).

The coverage with the Claydon, Farm system and Sumo DTS were statistically similar with one another. In autumn 2015 (after the harvest of oilseed and when drilling the wheat) in Top Furze, the residue coverage was lowest with the Farm system (15%), was followed in ascending order by Sumo DTS (48%), Claydon (52%), Mzuri (67%) and Väderstad (82%). All the treatments were significantly different from one another. As Figure 6.1 demonstrates the lowest and highest levels of residue coverage were created with the two pass Farm system (Sumo Trio followed by Kuhn HR) on the wheat and the Väderstad system respectively. The coverage provided by the Claydon, Mzuri, Sumo DTS, and one-pass Farm system were not significantly different from each other but significantly different from the Farm system and Väderstad.

### 6.3.2 Plant density per unit area

In March 2014, in the oilseed rape plots in Snagsborough, the plant density in the Sumo DTS treatments (37 plants $m^{-2}$), Mzuri (36 plants $m^{-2}$) and Claydon (34 plants $m^{-2}$) were greater ($p = 0.05$) than that in Farm System (29 plants $m^{-2}$) and Väderstad plots (20 plants $m^{-2}$) (Table 6.4). In 2014-15 in the same field, the plant density for wheat was measured on 19 November 2014 and 25 February 2015. There was no treatment effect ($p > 0.05$) on plant density in November, but the pairwise comparisons picked up a lower plant population for the Väderstad than the Farm system and Sumo DTS. However in February 2015, the density was significantly highest (299 plants $m^{-2}$) in the Claydon treatment and lowest in the Väderstad treatment (232 plants $m^{-2}$).

Table 6.4. Plant density ($m^{-2}$) of oilseed rape or wheat in Snagsborough for all seasons

| Treatment | **2013-14 Oilseed** | **2014-15 Wheat** | | **Difference Wheat** | **2015-16 Oilseed** | | **Difference Oilseed** |
|---|---|---|---|---|---|---|---|
| | 9-Mar-14 | 19-Nov-14 | 25-Feb-15 | Nov-Feb | 2-Oct-15 | 16-Oct-15 | Oct-Oct |
| Farm system | 29 b | 238 ab | 262 bc | +24 bc | 44 a | 49 a | +5 a |
| Claydon | 34 a | 221 bc | 299 a | +78 a | 39 b | 46 ab | +7 a |
| Mzuri | 36 a | 230 abc | 274 b | +44 b | 39 b | 43 c | +5 a |
| Sumo DTS | 37 a | 239 a | 251 c | +12 c | 29 c | 36 d | +7 a |
| Väderstad | 20 c | 220 c | 232 d | +12 c | 39 b | 47 ab | +8 a |
| Mean | 32 | 230 | 264 | +34 | 38 | 44 | 6 |

*Means with the same letter are not significantly different and apply to columns; Väderstad was replaced by Horsch in 2015-16

The plant density in the Mzuri and Farm system were statistically similar (262-274 plants $m^{-2}$) but higher ($p < 0.05$) than the Sumo DTS (251 plants $m^{-2}$) (Table 6.4). The increase between November 2014 and February 2015 was significantly greater for Claydon (26%) as compared to other treatments. However the basis for Claydon's higher value is not known. Mzuri did increase the plants significantly more (16%) than Sumo DTS (4.7%) and Väderstad (5.1%) which did not differ statistically with each other. In 2015-16, in Snagsborough the oilseed rape plant density was measured on 2 October and 16 October 2015. On October the greatest plant density was in the Farm system (44 plants $m^{-2}$) and the lowest was in the Sumo DTS treatment (29 plants $m^{-2}$). Claydon, Väderstad and Mzuri resulted in statistically similar plants per metre square ($p < 0.05$) of 37-39 plants $m^{-2}$. On 16 October, the results followed a similar pattern with Farm system and the Väderstad (47-49 plants $m^{-2}$) being significantly higher than Mzuri (43 plants $m^{-2}$) and Sumo DTS (36 plants $m^{-2}$), which had the lowest density (Table 6.4). The change was not statistically significant between 2 and 16 October 2015.

Table 6.5. Plant density ($m^{-2}$) of wheat and oilseed rape in Top Furze for all seasons

| Treatment | **2013-14 Wheat** | **2014-15 Oilseed** | **2015-16 Wheat** | | **Difference Wheat** |
|---|---|---|---|---|---|
| | 8-Mar-14 | 4-Oct-14 | 26-Nov-15 | 18-Jun-16 | Nov-Jun |
| Farm system | 161 ab | 19 bc | 290 a | 165 b | -125 b |
| Claydon | 166 ab | 23 a | 251 b | 180 ab | -71 a |
| Mzuri | 186 a | 23 a | 254 b | 207 ab | -47 a |
| Sumo DTS | 165 ab | 22 ab | 213 c | 183 ab | -30 a |
| Väderstad | 145 b | 19 c | 279 a | 215 a | -63 a |
| Mean | 164 | 21 | 257 | 190 | -67 |

*Means with the same letter are not significantly different and apply to columns; Väderstad was replaced by Horsch in 2014-15

In the first season in Top Furze (8 March 2014), Mzuri had a higher density of wheat plants (186 $m^{-2}$) than the Väderstad (145 $m^{-2}$). The density (161-165 $m^{-2}$) for Claydon, Sumo DTS and the Farm system were intermediate (Table 6.5). On 4 October 2014 in the same field, the density of oilseed rape plants was significantly lower for the Väderstad (19 $m^{-2}$) when compared to Mzuri, Claydon and Sumo DTS (22-23 $m^{-2}$). The Farm system had lower plant counts (19 plants $m^{-2}$) than the Mzuri and Claydon. In the last season, for wheat in Top Furze on 26 November 2015, Sumo DTS had the lowest plant density (213 plants $m^{-2}$). Farm system and Väderstad possessed the highest density (279-290 m-

$^{2}$). Mzuri and Claydon gave significantly higher values (251-254 m$^{-2}$) than the Sumo DTS, but lower than the Farm system and Väderstad. The wheat plant density in June 2016 was less than that in November 2015 (six weeks after drilling), suggesting plant mortality during the year. Whereas the plant density of the Farm system was similar to the Väderstad in November 2015, by June 2016 the density in the Farm system (165 m$^{-2}$) was 23% less than in the Väderstad plots (215 m$^{-2}$) (Table 6.5). The analysis of variance between November 2015 and June 2016 showed that the Farm system reduced the plants m$^{-2}$ by 125 which was significantly more than the other treatments (range of reduction 30-71 plants m$^{-2}$). This was a result of blackgrass infestation which showed a greater (but not significant) increase under the Farm system (Table 6.7, section 6.3.4).

### *6.3.3* Normalized Difference Vegetation Index (NDVI)

On 4 April 2014 for the oilseed rape in Snagsborough, the analysis of variance showed that the Sumo DTS, Claydon and Mzuri had significantly higher values for NDVI (0.85-0.86) than the Farm system (0.69) and Väderstad (0.67) (Table 6.6). These lower values match the lower plant densities found with the Farm system and the Väderstad (Table 6.4).

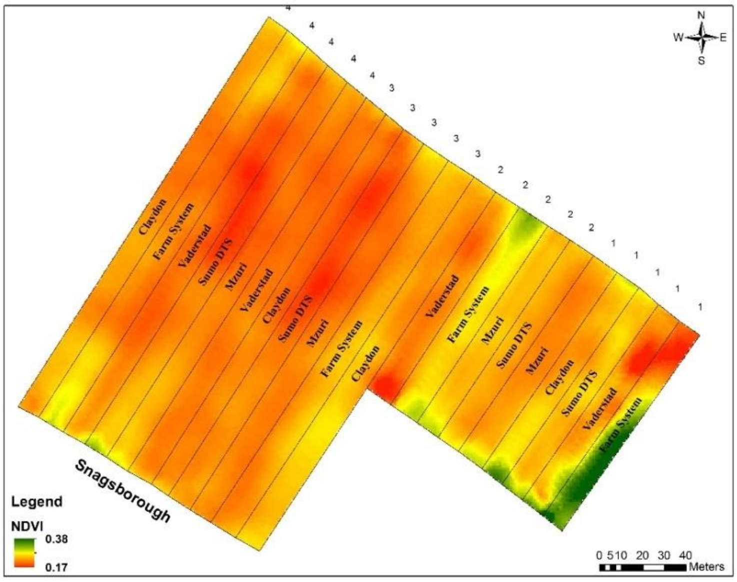
Table 6.6. Mean NDVI significant values ($p<0.05$) per tillage treatment in 2013-14, 2014-15, and 2015-16.

| Treatment | **2013-14** | | **2014-15** | | **2015-16** |
|---|---|---|---|---|---|
| | 4 April 14 | | 6 Mar 15 | 29 May 15 | 9 Dec 15 |
| | Snagsb'gh Oilseed | Top Furze Wheat | Snagsb'gh Wheat | Snagsbor'gh Wheat | Snagsbor'gh Oilseed |
| Farm system | 0.69 b | 0.35 b | 0.23 bc | 0.45 a | 0.15 b |
| Claydon | 0.86 a | 0.37 c | 0.26 ab | 0.40 c | 0.20 a |
| Mzuri | 0.85 a | 0.42 a | 0.22 c | 0.41 bc | 0.05 c |
| Sumo DTS | 0.86 a | 0.39 b | 0.22 c | 0.40 c | 0.02 c |
| Väderstad | 0.67 b | 0.37 c | 0.27 a | 0.44 ab | 0.16 ab |
| Mean | 0.78 | 0.38 | 0.24 | 0.42 | 0.11 |

*Means with the same letter are not significantly different and apply to columns; Väderstad was replaced by Horsch in 2014-15 in Top Furze & 2015-16 in Snagsborough

In Snagsborough on 6 March 2015, under wheat, the Väderstad gave a higher NDVI value (0.27) than the Farm system, Sumo DTS, and Mzuri (0.22-0.23). The NDVI in the Claydon treatment (0.26) was similar to Väderstad and Farm system, but significantly higher than the Sumo DTS and Mzuri. By 29 May 2015 the ranking had changed. The Väderstad continued to have a high NDVI (0.44), but it was now similar to that for the Farm system (0.45), which in turn was greater than that for the Mzuri, Claydon, and Sumo DTS (0.40-0.41). The change in NDVI between May and March 2015 in Snagsborough was greater for the Farm system (0.21) than the Väderstad (0.17) and Claydon (0.14). Between March and May 2015, the Farm system plots increased crop canopy (greener areas) more than the Väderstad and Claydon plots (Figure 6.2).

a) March 2015



b) May 2015

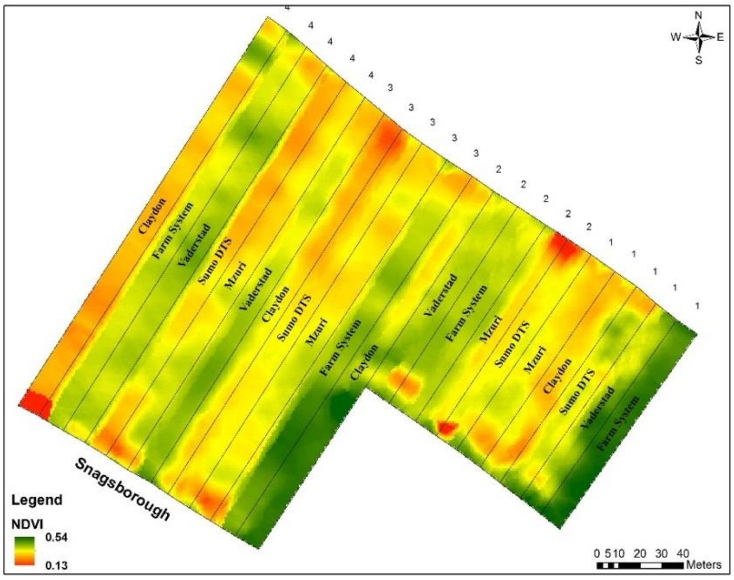


Figure 6.2. NDVI spatial distribution in Snagsborough (wheat) in a) March 2015 and b) May 2015

That was not an effect of row spacing because Farm system had 500 mm rows while Väderstad and Claydon 125 and 300 mm respectively. On 9 December 2015, the NDVI values, as expected, were low because the oilseed rape crop was still young. The lowest values were found with the Mzuri and the Sumo DTS. This is associated with these two crops being drilled two weeks later than the other three treatments (Table 6.6). The NDVI in Top Furze for the wheat in April 2014 showed that the Mzuri value of 0.42 was significantly the highest of all treatments, while the Farm system had significantly the lowest value (0.35) (Table 6.6). The Sumo DTS value of 0.39 was lower than the Mzuri, but higher than the Väderstad and Claydon (0.37 and 0.37).

### 6.3.4 Blackgrass spatial distribution and density per unit area

Blackgrass distribution was assessed in 2013-14 and 2015-2016 in the wheat crop grown in Top Furze. On both occasions, the density of blackgrass plants did not vary with treatment, but the density varied between the two years. In 2013-14, the coefficient of variation for the heads per metre square was 110% with mean values ranging from 85 to 204 heads $m^{-2}$. In 2015-16, the coefficient of variation was 74%, with mean values ranging from 248 to 432 heads $m^{-2}$.

Each treatment showed an increase in the density of blackgrass heads per metre square between season 1 and season 3, but an ANOVA indicated no significant treatment effect due to the high variability. Although the treatment differences were not significant, the highest change in blackgrass heads occurred with the Farm system (Figure 6.3).

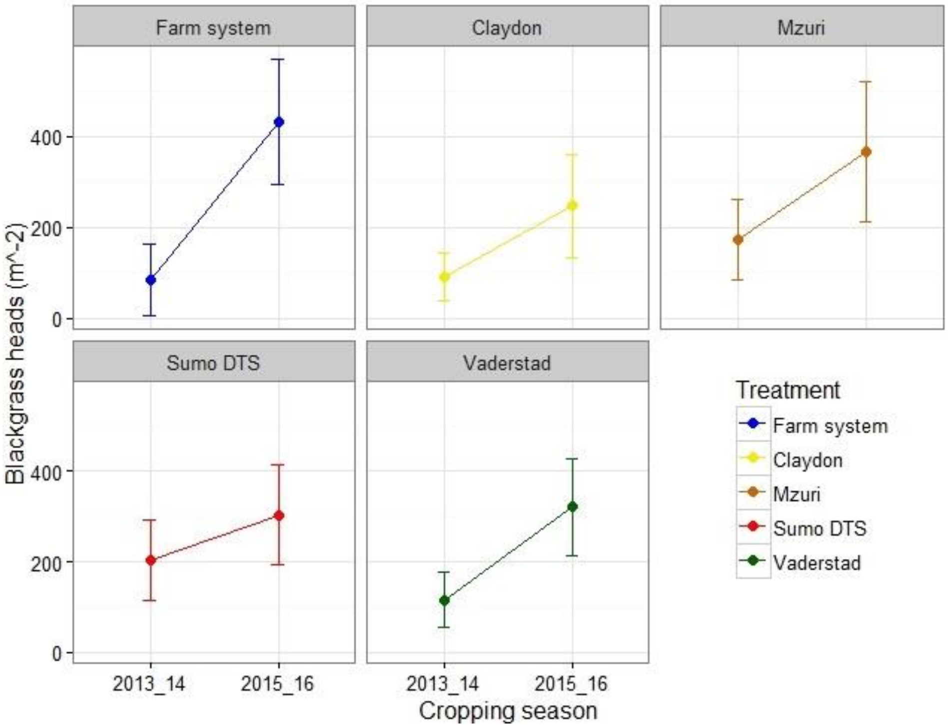


Figure 6.3. Mean blackgrass heads per square metre for each treatment in Top Furze for both seasons (error bars show standard error of the mean)

The statistical analysis indicated no significant treatment effects in Top Furze on the spatial extent of blackgrass infested areas (m$^2$). For the first season, values ranged from 94 to 265 m$^2$ with the coefficient of variation being 103%. For the last season, values ranged from 268 to 404 m$^2$ with a coefficient of variation of 78%. Although the area of blackgrass increased from 2013-14 to 2015-16 (Figure 6.4) the change per treatment was not significant due to the high variation.

The greatest (although non-significant) increase in blackgrass area occurred in the Farm system, with new blackgrass areas appearing in the two eastern blocks (Figure 6.4). In summary, all the statistical analysis showed no significant treatment effect, with the variability being higher in the first season (Table 6.7). The blackgrass areas were also expressed as a proportion of the total tilled area in Top Furze in 2013-14 and 2015-16 (Table 6.8). The proportion of the area affected by blackgrass increased in each treatment with the greatest increase occurring in the Farm system (+13%). The total blackgrass infested area in Top Furze was doubled in year 3.

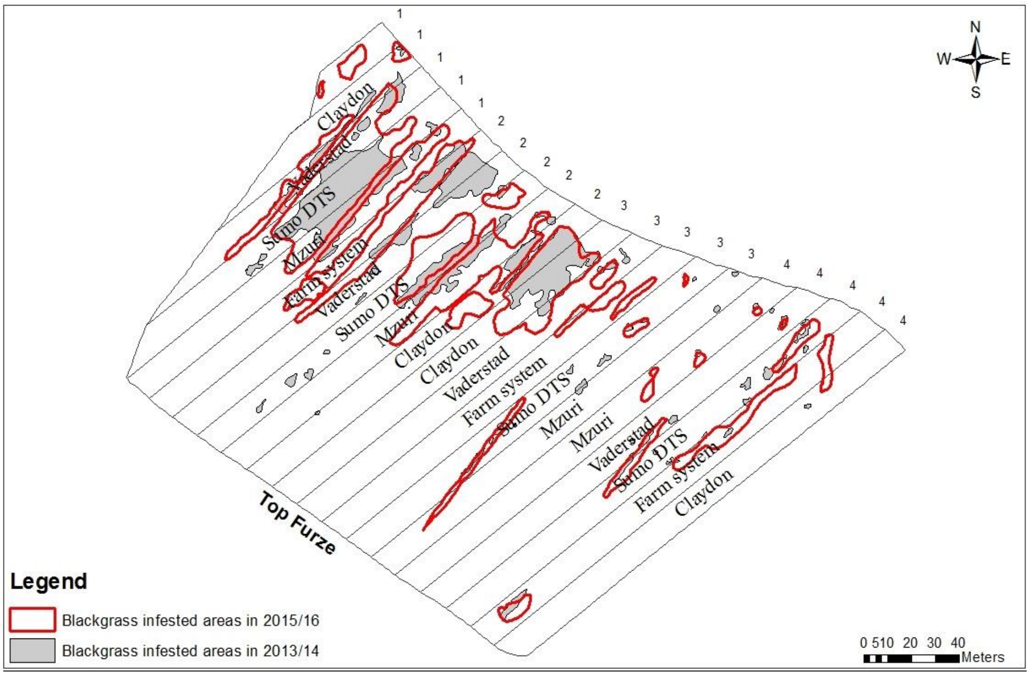


Figure 6.4. Blackgrass infested areas in Top Furze for 2013-14 and 2015-16

Table 6.7. Analysis of variance for blackgrass infested areas (m$^2$) and heads (m$^{-2}$) in Top Furze in 2013-14 and 2015-16.

| Treatment | 2013-14 | | 2015-16 | | Change | |
|---|---|---|---|---|---|---|
| | Area (m$^2$) | Heads (m$^{-2}$) | Area (m$^2$) | Heads (m$^{-2}$) | Area (m$^2$) | Heads (m$^{-2}$) |
| Farm system | 94 a | 84 a | 329 a | 432 a | +235 a | +348 a |
| Claydon | 183 a | 91 a | 286 a | 247 a | +102 a | +156 a |
| Mzuri | 157 a | 173 a | 356 a | 366 a | +199 a | +193 a |
| Sumo | 265 a | 204 a | 404 a | 302 a | +138 a | +98 a |
| Väderstad | 152 a | 116 a | 268 a | 321 a | +116 a | +205 a |
| cvar (%) | 103 | 110 | 78 | 74 | - | - |

*Means with the same letter are not significantly different and apply per column

Table 6.8. Proportional blackgrass infestation (%) as per total area of treatment in Top Furze in 2013-14 and 2015-16.

| Treatment | 2013-14 | 2015-16 |
|---|---|---|
| Farm system | 5.0 | 18.0 |
| Claydon | 10.0 | 14.8 |
| Mzuri | 7.0 | 16.0 |
| Sumo DTS | 12.0 | 18.2 |
| Väderstad | 7.3 | 13.0 |
| Mean | 8.2 | 16.0 |

### 6.3.5 Crop yield

#### *6.3.5.1 Snagsborough field*

Snagsborough field was drilled to oilseed rape in 2013-14, to wheat in 2014-15, and back to oilseed rape in 2015-16. In 2013-14, when Snagsborough was drilled to oilseed rape, there was no significant treatment effect on the mean measured yield (4.4 t ha$^{-1}$) or mean corrected yield (4.6 t ha$^{-1}$) (Table 6.9). The histogram shows yield frequencies both from data obtained from the clear and close to headlands areas (Figure 6.5).

Table 6.9. Mean oilseed rape yield for 2013-14 cropping season in Snagsborough

| Treatment | Measured yield (t ha$^{-1}$) | Corrected yield (t ha$^{-1}$) |
|---|---|---|
| Farm system | 4.56 a | 4.74 a |
| Claydon | 4.17 a | 4.38 a |
| Mzuri | 4.54 a | 4.74 a |
| Sumo DTS | 4.60 a | 4.81 a |
| Väderstad | 4.20 a | 4.38 a |
| Mean | 4.41 | 4.61 |
| LSD | 0.71 | 0.75 |
| cvar (%) | 25.5 | 19.4 |

*Means with the same letter are not significantly different and apply to columns

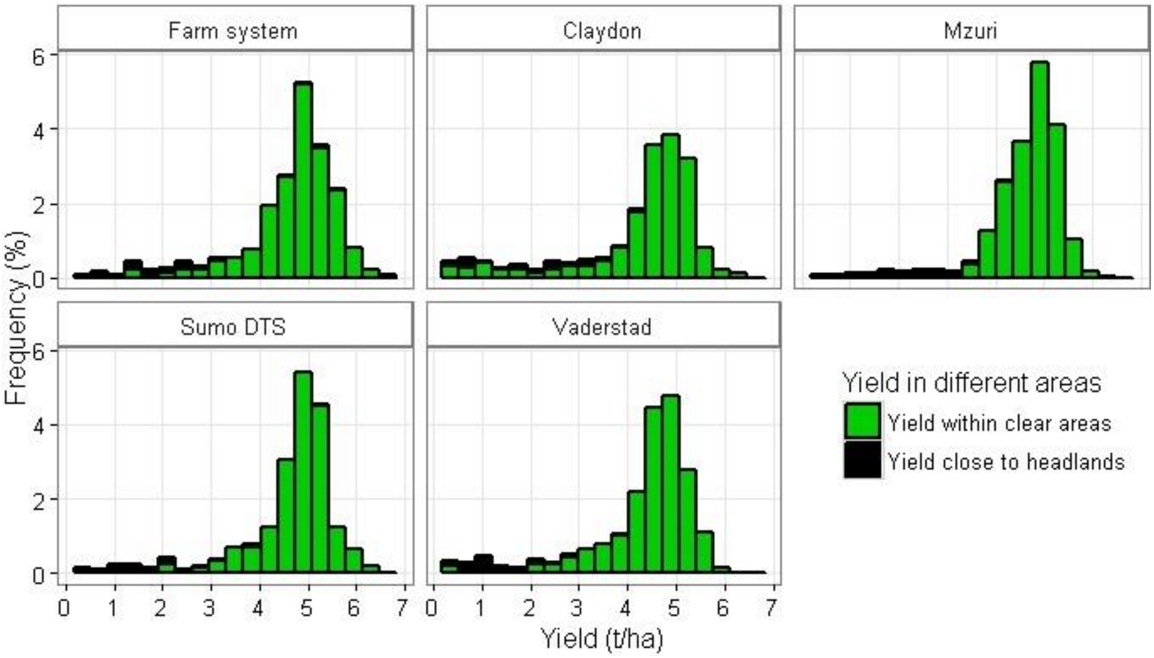


Figure 6.5. Snagsborough 2013-14 oilseed rape yields i) within clear areas (green) and ii) close to headlands (black)

In 2014-15, Snagsborough was drilled to wheat. The yields showed no significant difference between treatments (p=0.05). However if a less rigorous statistical standard is applied for example p=0.15, then the Farm system corrected yield (11.63 t ha$^{-1}$) was greater than that obtained with the Claydon (11.02 t ha$^{-1}$) (Table 6.10). Figure 6.6 illustrates the frequency (%) of all the wheat yield points for each treatment in 2014-15 for Snagsborough.

Table 6.10. Mean wheat yield for 2014-15 cropping season in Snagsborough

| Treatment | Measured yield (t ha$^{-1}$) | Corrected yield (t ha$^{-1}$) | |
|---|---|---|---|
| Farm system | 11.35 a | 11.63 a | *a* |
| Claydon | 10.90 a | 11.02 a | *b* |
| Mzuri | 10.77 a | 11.12 a | *ab* |
| Sumo DTS | 11.05 a | 11.41 a | *ab* |
| Väderstad | 11.00 a | 11.27 a | *ab* |
| Mean | 11.03 | 11.29 | |
| p level | 0.05 | 0.05 | *0.15* |
| LSD | 0.75 | 0.80 | |
| cvar (%) | 14.3 | 8.5 | |

*Means with the same letter are not significantly different at the specified p level and apply to columns

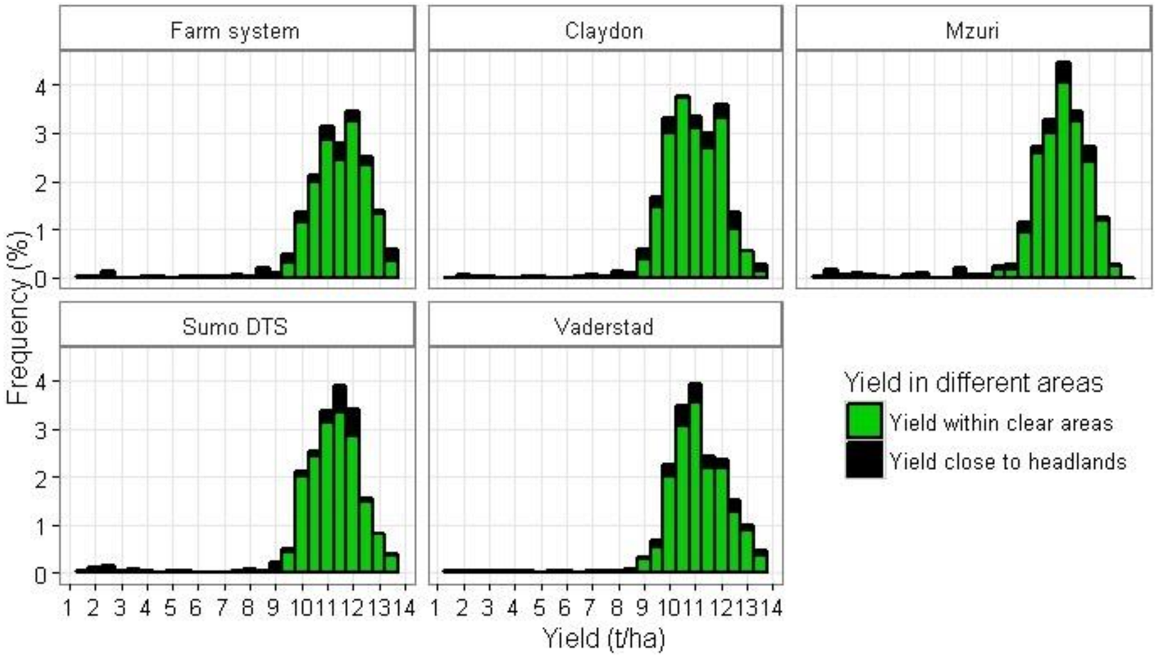


Figure 6.6. Snagsborough 2014-15 wheat yields i) within clear areas (green) and ii) close to headlands (black)

In 2015-16, both the measured and corrected yields of oilseed rape were lower for the Sumo DTS (3.32 and 3.43 t ha$^{-1}$ respectively) than that (4.0-4.5 t ha$^{-1}$) for all other treatments (Table 6.11). Sumo DTS and Mzuri treatments were drilled 10 days later than the other treatments, but only the Sumo DTS resulted in the significantly lower yield. Figure 6.7 shows the frequency histogram of the oilseed rape yields with and without the headlands confounding factor.

Table 6.11 Mean oilseed yield for 2015-16 cropping season in Snagsborough

| Treatment | Measured yield (t ha$^{-1}$) | Corrected yield (t ha$^{-1}$) |
|---|---|---|
| Farm system | 4.37 a | 4.54 a |
| Claydon | 4.34 a | 4.48 a |
| Mzuri | 4.04 a | 4.14 a |
| Sumo DTS | 3.32 b | 3.43 b |
| Väderstad | 4.24 a | 4.43 a |
| Mean | 4.06 | 4.20 |
| LSD | 0.54 | 0.57 |
| cvar (%) | 23.9 | 20.1 |

*Means with the same letter are not significantly different and apply to columns
Väderstad was replaced by Horsch

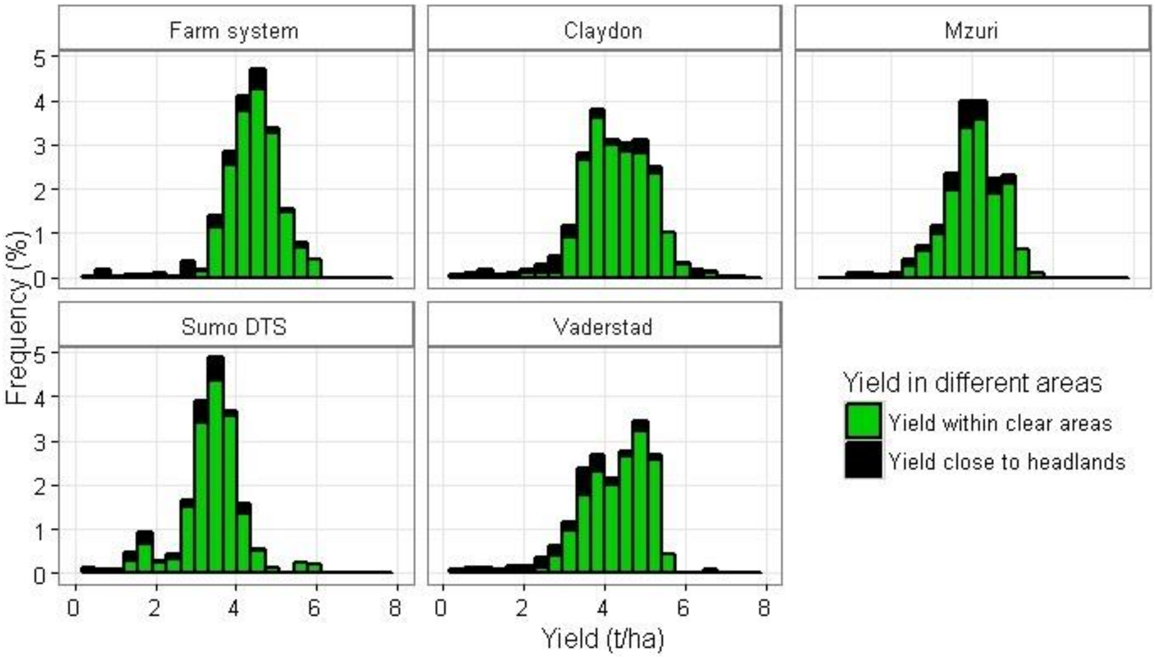


Figure 6.7. Snagsborough 2015-16 oilseed rape yields i) within clear areas (green) and ii) close to headlands (black)

### 6.3.6 Yield synopsis in Snagsborough for all cropping seasons

In Snagsborough as mentioned in section 6.2.6 measured yield referred to the yield obtained from the clear areas along with the yield data obtained close to headlands. Figure 6.5 to Figure 6.7 indicate that yield values close to the headlands were lower and their cases were less, than those in the centre of the field and the clear areas. Removing these values, reduced the co-efficient of variation of the remaining dataset by 6.1% in 2013-14, 5.8% in 2014-15, and 3.8% in 2015-16 (Table 6.12). In addition, the trend across seasons showed that all treatments achieved lower (but not significant) yields in years 2 and 3 as compared to the Farm system. In year 3 the Sumo DTS yielded 75% of the Farm system's yield and that difference was significant due to the delayed drilling. However for the same delay in drilling by Mzuri was not associated with significant lower yields (Table 6.12).

Table 6.12. Summary table the corrected yields with the coefficient of variation for each cropping season in Snagsborough

| | 2013-14 | 2014-15 | 2015-16 |
|---|---|---|---|
| Treatment | Oilseed rape (t ha$^{-1}$) | Wheat (t ha$^{-1}$) | Oilseed rape (t ha$^{-1}$) |
| Farm system | 4.74 a **(100)** | 11.65 a **(100)** | 4.54 a **(100)** |
| Claydon | 4.38 a (92) | 11.02 a (94) | 4.48 a (98) |
| Mzuri | 4.74 a (100) | 11.12 a (95) | 4.14 a (91) |
| Sumo DTS | 4.81 a (101) | 11.40 a (98) | 3.43 b (75) |
| Väderstad | 4.38 a (92) | 11.27 a (97) | 4.43 a (97) |
| Mean | 4.61 | 11.29 | 4.20 |
| LSD | 0.75 | 0.80 | 0.57 |
| cvar (%) | 19.4 | 8.5 | 20.1 |

*Means with the same letter are not significantly different and apply to columns; Väderstad was replaced by Horsch in 2015-16; Propertion of Farm system is shown in brackets

Figure 6.8 depicts the spatial distribution of yield in Snagsborough for a) the oilseed rape in 2013-14, b) the wheat in 2014-15 and c) the oilseed rape in 2015-16. The greener the areas, the higher the yields. Yellow and red areas correspond to moderate and low yields across the field. From  is verified that the lower yield areas in red did belong to the Sumo DTS plots in 2015-16. Also, the yields in general were lower closer to the field borders (headlands) for all the cropping seasons.

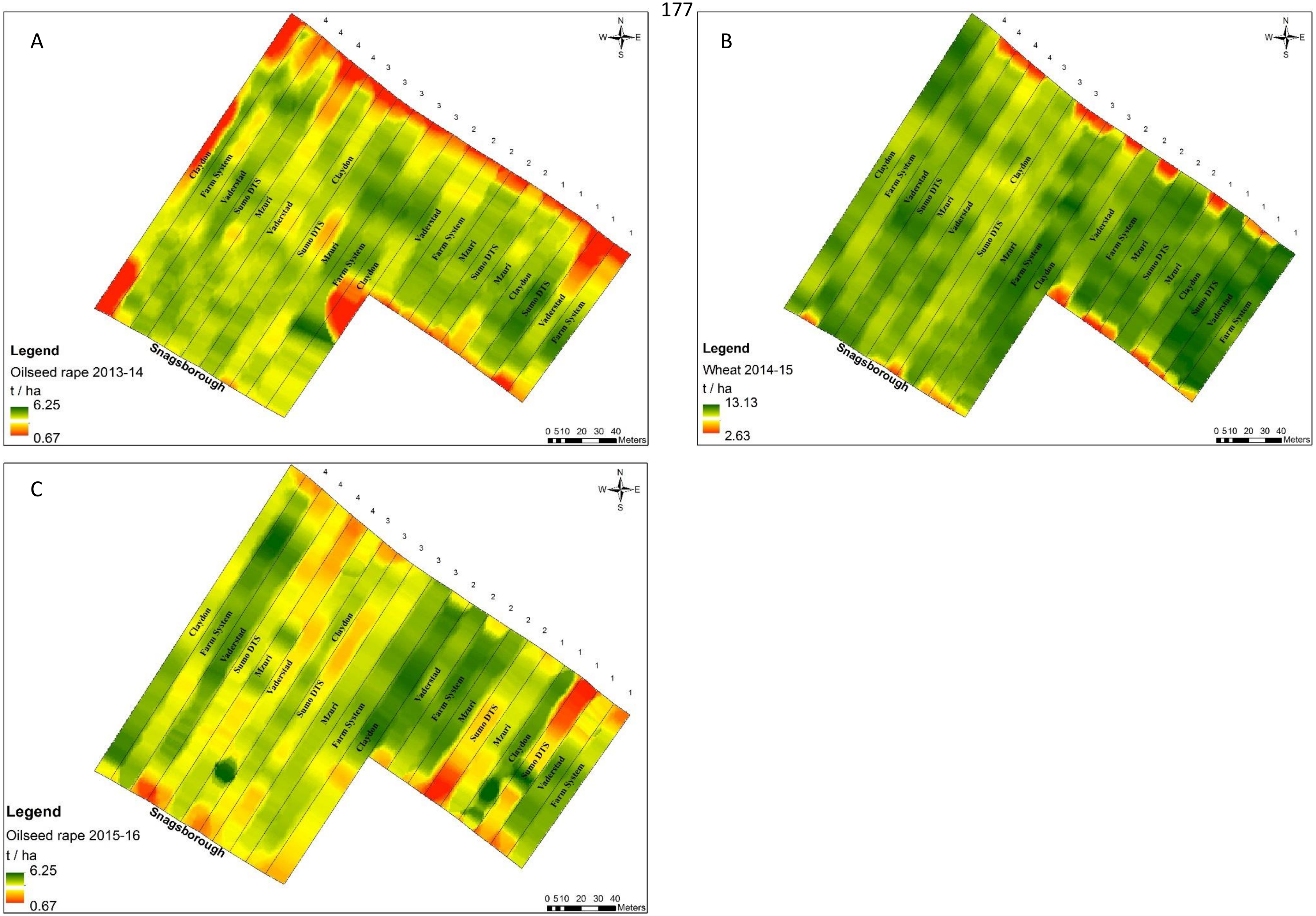


Figure 6.8. Spatial distribution of yield in Snagsborough; A) oilseed rape in 2013-14, B) wheat in 2014-15 and C) oilseed rape in 2015-16

#### *6.3.6.1 Top Furze field*

The Top Furze field was drilled to wheat in 2013-14, oilseed rape in 2014-15 and wheat again in 2015-16. In 2013-14 the mean uncorrected yield for all treatments was 10.13 t ha$^{-1}$; excluding headlands increased the mean yield to 10.42 t ha$^{-1}$ and reduced the co-efficient of variation from 24.7% to 21.6% (Table 6.13). Excluding the tramlines had a smaller effect on yields and did not reduce the co-efficient of variation. Excluding the blackgrass areas increased the mean yield to 10.56 t ha$^{-1}$; excluding the headlands, tramlines, and blackgrass areas increased the mean yield to 11.05 t ha$^{-1}$ and reduced the coefficient of variation to 18.4%.

Table 6.13. Mean wheat yields for 2013-14 cropping season in Top Furze

| Treatment | Measured yield (t ha$^{-1}$) | Yield excluding headlands (t ha$^{-1}$) | Yield excluding tramlines (t ha$^{-1}$) | Yield excluding blackgrass (t ha$^{-1}$) | Corrected yield (t ha$^{-1}$) | |
|---|---|---|---|---|---|---|
| Farm system | 9.66 a | 9.94 a | 10.14 a | 10.03 a | 10.47 a | *b* |
| Claydon | 9.83 a | 10.25 a | 10.00 a | 10.31 a | 11.02 a | *ab* |
| Mzuri | 10.59 a | 10.81 a | 10.71 a | 11.05 a | 11.39 a | *a* |
| Sumo DTS | 9.90 a | 10.11 a | 9.83 a | 10.53 a | 11.01 a | *ab* |
| Väderstad | 10.65 a | 11.01 a | 10.62 a | 10.89 a | 11.38 a | *a* |
| Mean | 10.13 | 10.42 | 10.26 | 10.56 | 11.05 | |
| p level | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.15 |
| LSD | 1.49 | 1.74 | 1.51 | 1.84 | 2.08 | |
| cvar (%) | 24.7 | 21.6 | 25.6 | 22.9 | 18.4 | |

*Means with the same letter are not significantly different at the specified p level and apply to columns

In 2013-14, there was no significant treatment effect (p=0.05) on yield. However if a less rigorous statistical standard is applied, for example p=0.15, the corrected yield for Väderstad and Mzuri was greater than that of the Farm system (Table 6.13). Mzuri, Väderstad, Claydon and Sumo DTS resulted in similar corrected yields with one another (11.39, 11.38, 11.02 and 11.01 t ha$^{-1}$ respectively) at the same level of significance (p=0.15). Figure 6.9 depicts the yield points affected by confounding factors: the headlands (black), the tramlines (red) and areas of blackgrass (purple). The yields and relatively proportion of the areas affected by these confounding factors are shown in Figure 6.10. The data points in the headlands resulted in significantly lower yields.

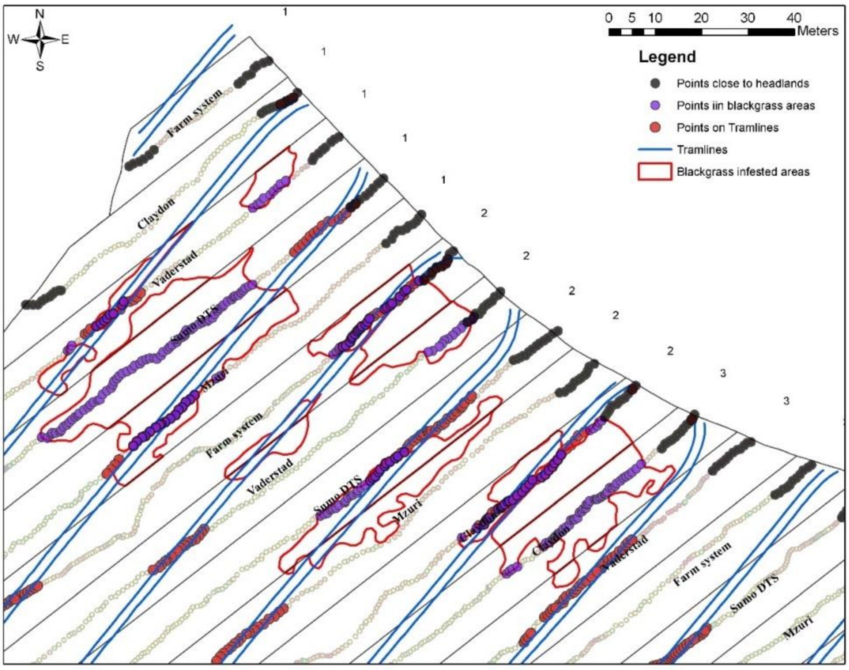


Figure 6.9. Map extract of Top Furze field in 2013-14 showing all data points, including those corresponding to confounding factors

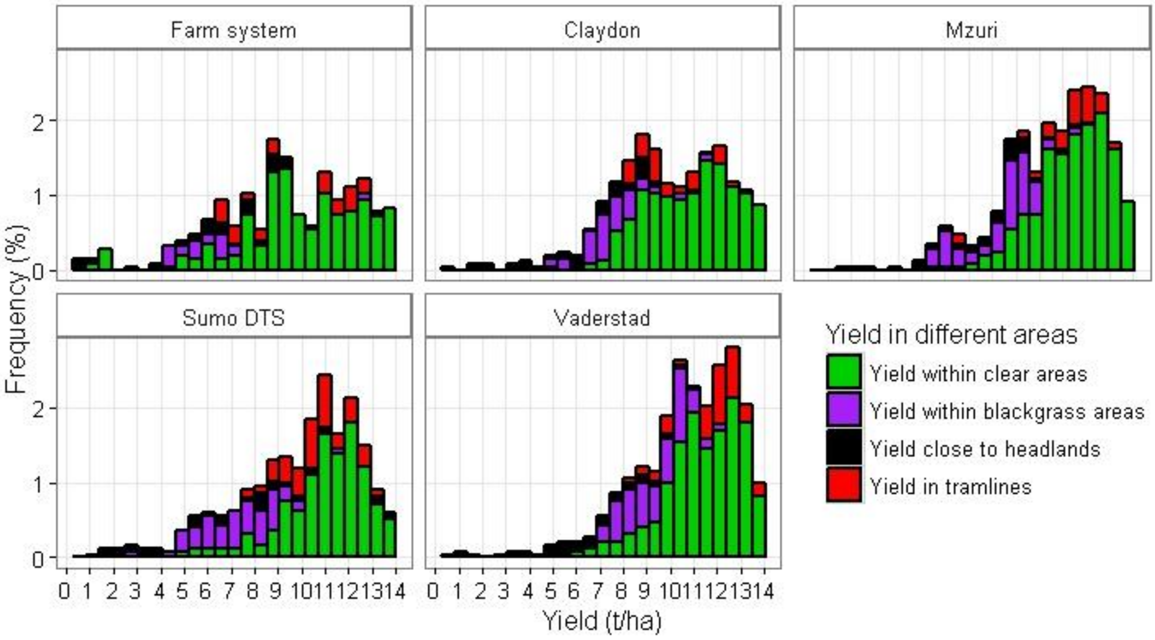


Figure 6.10. Top Furze 2013-14 wheat yields i) within clear areas (green), ii) within blackgrass areas (purple), iii) close to headlands (black) and iv) yield in tramlines (red)

In 2014-15, in the oilseed rape crop, blackgrass was not a problem. When the headlands were excluded, the yield in the Mzuri treatment (4.88 t ha$^{-1}$) was greater than that of Claydon and Sumo DTS (4.16 t ha$^{-1}$) (Table 6.14). Assuming a p value of 0.15, the corrected yield in the Mzuri and Väderstad treatments (4.94 & 4.77 t ha$^{-1}$ respectively) were greater than for the Claydon treatment (4.30 t ha$^{-1}$) (Table 6.14).

Table 6.14. Mean oilseed rape yields for 2014-15 cropping season in Top Furze

| Treatment | Measured yield (t ha$^{-1}$) | Yield excluding headlands (t ha$^{-1}$) | Yield excluding tramlines (t ha$^{-1}$) | Corrected yield (t ha$^{-1}$) | |
|---|---|---|---|---|---|
| Farm system | 4.15 a | 4.41 ab | 4.23 a | 4.55 a | *abc* |
| Claydon | 4.03 a | 4.16 b | 4.13 a | 4.30 a | *c* |
| Mzuri | 4.71 a | 4.88 a | 4.73 a | 4.94 a | *a* |
| Sumo DTS | 4.03 a | 4.16 b | 4.16 a | 4.33 a | *bc* |
| Väderstad | 4.53 a | 4.69 ab | 4.57 a | 4.77 a | *ab* |
| Mean | 4.29 | 4.46 | 4.36 | 4.57 | |
| p level | 0.05 | 0.05 | 0.05 | 0.05 | 0.15 |
| LSD | 0.71 | 0.65 | 0.71 | 0.66 | |
| cvar(%) | 33.0 | 30.4 | 32.4 | 29.0 | |

*Means with the same letter are not significantly different at the specified p level and apply to columns; Väderstad was replaced by Horsch

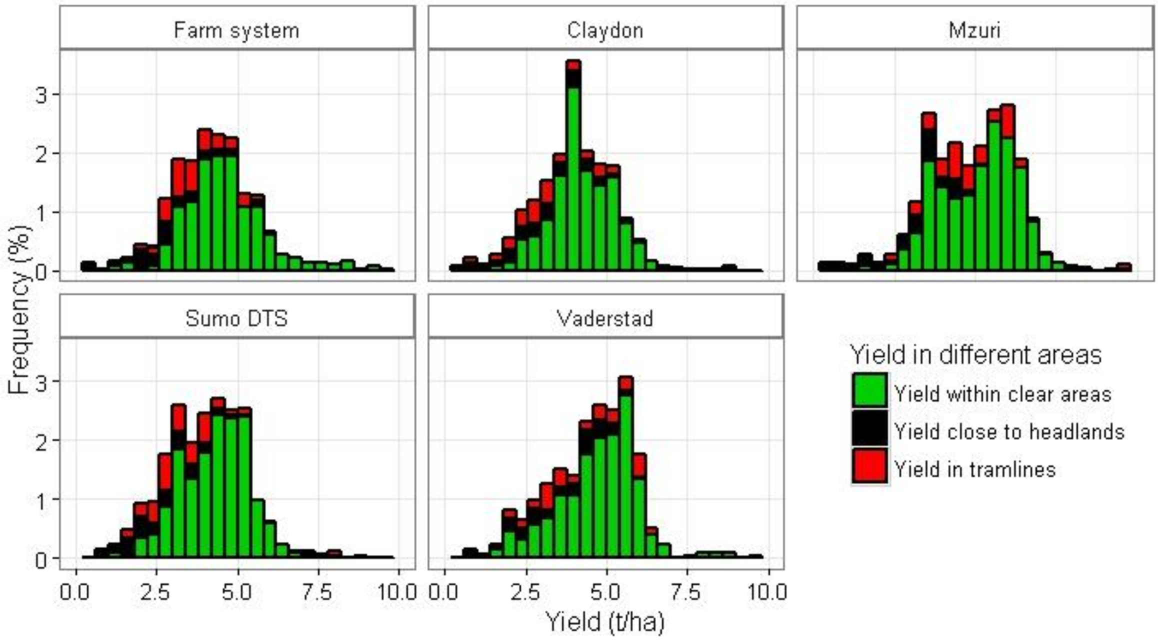


Figure 6.11. Top Furze 2014-15 oilseed rape yields i) within clear areas (green), ii) close to headlands (black) and iii) yield in tramlines (red)

In the last cropping season (2015-16), Top Furze was again drilled to wheat. There was no significant treatment effect on measured or corrected yields. The corrected yields, which had the lowest coefficient of variation of 21%, ranged from 8.71 to 9.51 t ha$^{-1}$ Table 6.15; Figure 6.12). The variability in yield was reduced by removing yields from headlands and areas of blackgrass infestation; removing the tramlines tended to increase the variability.

Table 6.15. Mean wheat yields for 2015-16 cropping season in Top Furze

| Treatment | Measured yield (t ha$^{-1}$) | Yield excluding headlands (t ha$^{-1}$) | Yield excluding tramlines (t ha$^{-1}$) | Yield excluding blackgrass (t ha$^{-1}$) | Corrected yield (t ha$^{-1}$) |
|---|---|---|---|---|---|
| Farm system | 8.15 a | 8.73 a | 8.01 a | 8.35 a | 9.18 a |
| Claydon | 7.30 a | 7.66 a | 7.14 a | 7.95 a | 8.71 a |
| Mzuri | 8.00 a | 8.22 a | 7.97 a | 8.88 a | 9.51 a |
| Sumo DTS | 7.45 a | 7.68 a | 7.45 a | 8.06 a | 8.80 a |
| Väderstad | 8.12 a | 8.53 a | 8.04 a | 8.51 a | 9.26 a |
| Mean | 7.80 | 8.16 | 7.72 | 8.35 | 9.09 |
| LSD | 1.31 | 1.42 | 1.42 | 1.65 | 1.64 |
| cvar (%) | 35.8 | 31.5 | 37.6 | 30.1 | 21.1 |

*Means with the same letter are not significantly different and apply to columns

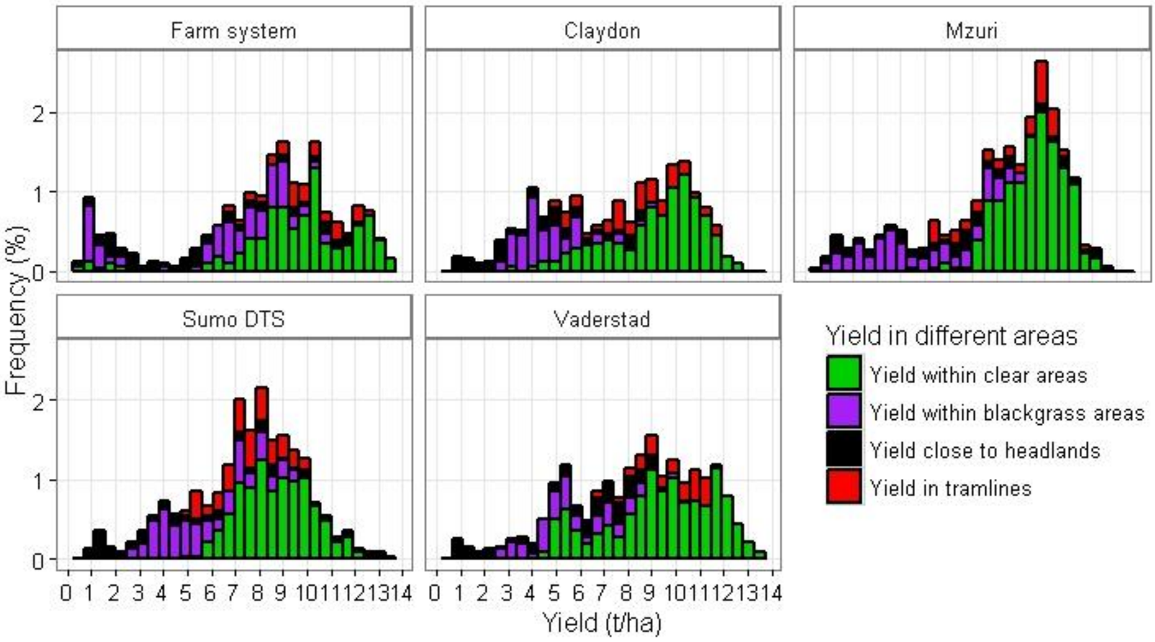


Figure 6.12. Yield synopsis in Top Furze for all cropping seasons in Top Furze 2015-16 wheat yields i) within clear areas (green), ii) within blackgrass areas (purple), iii) close to headlands (black) and iv) yield in tramlines (red)

Top Furze gave highly variable yields, which was partly due to the blackgrass areas and headlands. Figure 6.13 illustrates the spatial distribution of yield within each cropping season, including the main confounding factor (the blackgrass infestation). Red and green colours indicate low and high yields respectively.

Figure 6.13A shows measured wheat yields in 2013-14, with blackgrass areas (purple polygons), where the yield was low, as indicated by the results in Table 6.13. Figure 6.13C, shows the wheat yield of 2015-16, where blackgrass areas (purple polygons) are more extensive than in 2013-14. Thus, areas of low yields (red colour) are more noticeable across the field. Table 6.16 demonstrates that, alongside the increase in area of blackgrass infestation in Top Furze, a wheat yield reduction of 20% took place between 2013-14 and 2015-16. In addition, the trend across seasons showed that within all years Mzuri and Väderstad achieved, between 3 and 8% yield excess (not statistically significant) as compared to the Farm system. Whereas Claydon and Sumo DTS yielded between 4 to 5% lower (not significant) than Farm system in the last two years and 5% higher in year 1 (Table 6.16).

Table 6.16. Summary table of the corrected yields for each treatment per cropping season with the coefficient of variation in Top Furze

| | 2013-14 | 2014-15 | 2016-16 |
|---|---|---|---|
| Treatment | Wheat (t ha$^{-1}$) | Oilseed rape (t ha$^{-1}$) | Wheat (t ha$^{-1}$) |
| Farm system | 10.47 a **(100)** | 4.55 a **(100)** | 9.18 a **(100)** |
| Claydon | 11.02 a (105) | 4.30 a (94) | 8.71 a (95) |
| Mzuri | 11.39 a (108) | 4.94 a (108) | 9.51 a (103) |
| Sumo DTS | 11.01 a (105) | 4.33 a (95) | 8.80 a (96) |
| Väderstad | 11.38 a (108) | 4.77 a (105) | 9.26 a (100) |
| Mean | 11.05 | 4.57 | 9.09 |
| LSD | 2.08 | 0.66 | 1.64 |
| cvar (%) | 18.4 | 29.0 | 21.1 |

*Means with the same letter are not significantly and apply to columns; Väderstad was replaced by Horsch in 2015-16; Proportion of Farm system is shown in brackets

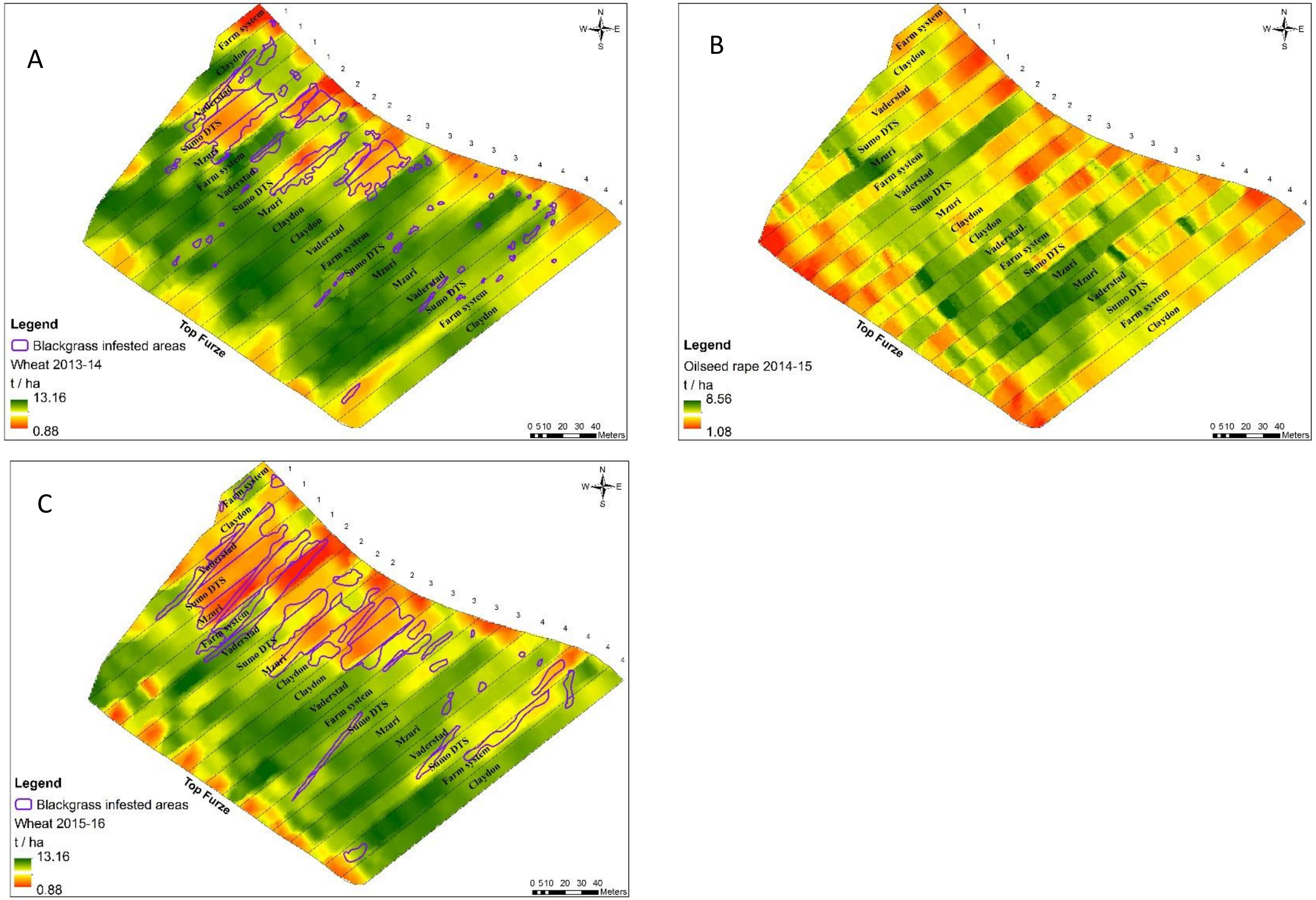


Figure 6.13. Spatial distribution of yield and blackgrass infested areas in Top Furze; A) wheat in 2013-14, B) oilseed rape in 2014-15 and C) wheat in 2015-16

### 6.3.7 Harvest index

Harvest Index (*HI*) is defined as the ratio between grain yield on a dry-weight basis and the total above ground dry matter at harvest. It was measured in 2013-14 as a representative sample for each field. Dry matter yield in 2013-14 was calculated assuming a moisture content of 15% in wheat and 8% in oilseed rape. The mean dry matter yield for oilseed rape was 4.6 t ha$^{-1}$ and the total above ground dry matter 15.3 t ha$^{-1}$ which resulted in a harvest index of 0.30. The harvest index for the wheat was 0.41, based on a mean grain dry matter yield of 11.0 t ha$^{-1}$ with an above ground dry matter of 26.4 t ha$^{-1}$ (Table 6.17).

Table 6.17. Total above ground dry matter production and estimated harvest index of oilseed rape and winter wheat in 2013-14

| | **Oilseed rape** | **Wheat** |
|---|---:|---:|
| Dry matter yield (t ha$^{-1}$) | 4.6 | 11.0 |
| Above-ground dry matter (t ha$^{-1}$) | 15.3 | 26.4 |
| Harvest index | 0.30 | 0.41 |

### 6.3.8 Oil content

The oil content of the oilseeds was also measured after harvest in 2013-14 and 2014-15 (following the British ISO reference method). The results showed that the percentage of oil in a sample of 10 g of seeds was 34% in 2013-14 which was lower than the reference value of 40%. As HGCA (2006) reports, most buyers of oilseed rape in the UK pay an oil premium of 1.5% for every 1% of oil content above 40%. A similar deduction is made for loads below 40%. The extraction was carried out only for a single representative sample taken in each field. In the second season (2014-15), oil extraction was carried out on five samples, one representative sample from each treatment plot of the third block, and the outcome ranged from 37 to 41% oil content.

## 6.4 Discussion

### 6.4.1 Crop residue

The tillage treatments leaving the greatest cover of surface crop residue were the Väderstad Seed Hawk and Rapid, while the lowest cover was attributed to the double pass Farm system (Figure 6.1). The high values of the Väderstads can be related to their shallow working depths (25 mm) which causes less soil disturbance than the other treatments. By contrast the Farm system in wheat caused the highest amount of soil disturbance (Chapter 4 and 5). The first pass of the Farm system, the Sumo Trio, works deeper (200 mm) than other systems and the Kuhn HR seed drill includes a power harrow which mixes the soil surface.

Shallow and low disturbance tillage systems, such as the Väderstad Seed Hawk and Rapid, accumulated the greatest amount of crop residues at the soil surface which were above 70% in both fields and years. The two pass Farm system in wheat left 15 and 17% surface crop residue in year 1 and year 3 respectively. Tillage systems that result in crop residue values between 0 and 14% are not considered conservation systems by definition (section 2.2.1). Hence, the two-pass Farm system fell very close to the upper limit of the residue cover that conventional tillage systems could leave.

Consistent with the findings of López et al. (2003) and Olaoye (2001) the present study confirms that primary tillage operations had a major influence on crop residue. They demonstrated that both deep and two-three passes tillage systems resulted in less crop residue on the soil surface. Likewise, Rasnake & Rasnake (1983) also reported that the use of a chisel and disc can reduce residue on the surface by one-third while no-tillage leaves almost all of the residue on the soil surface.

### 6.4.2 Plant density

The seed rate for wheat was 300 m$^{-2}$ in years 1 and 2 and 375 m$^{-2}$ in year 3. In oilseed rape within all years seed rate was 50 seeds m$^{-2}$. In 2013-14 and 2014-15 in Snagsborough and Top Furze, the Väderstad Seed Hawk and Rapid led to lower plant densities than the other treatments (Table 6.4; Table 6.5).

These results suggest that the low level of soil disturbance with the Väderstad tend to result in a poorer rate of seedling establishment because of high surface bulk densities in September 2014 and 2015 as well high penetration resistances in most cases at surface level. Another potential reason is the poor soil to seed contact as both Väderstads operated very shallow while the Rapid, which was a disc drill, tended to bend (hair-pin) the last year’s residues into the slot, interfering this way with seed germination and/or seedling emergence. By contrast Arvidsson et al. (2014) reported that plant establishment was similar for shallow tillage and deep intense tillage systems. In fact Parvin et al. (2017) reported higher plant densities in shallow-tilled treatment as compared to deep tillage systems like moldboard plough. In year 3 in Snagsborough, the lowest plant density occurred with the Sumo DTS (Table 6.4). In this year, the low density initially achieved with the Sumo DTS can be explained by later drilling (Table 6.1) as the plant density was still increasing between 2 October and 16 October 2015 (Table 6.4). Likewise in year 3 in Top Furze, when the drilling date was also delayed for the Sumo DTS, it was also associated with the lowest plant density (Table 6.5).

### 6.4.3 NDVI

In April 2014, low values for NDVI with the Väderstad Seed Hawk on oilseed rape and the Väderstad Rapid on wheat (Table 6.6) can be explained by the low plant densities measured one month earlier as discussed above (section 6.4.2). Low plant densities will tend to result in lower levels of light interception.

All the treatments were drilled at the same date in 2014 (Table 6.1) and the higher NDVI change for the Farm system could be explained by stronger plant growth associated with the surface bulk density (0-50 mm) for the Farm system in 2014-15 in Snagsborough being significant lower (1.17 Mg $m^{-3}$) than the rest of the treatments (range: 1.28 - 1.34 Mg $m^{-3}$) (Section 5.3.1). This could have enabled an easier path for the roots through the soil. In December 2015 in Snagsborough, the low NDVI with the Mzuri and Sumo DTS (Table 6.6) can be explained by their delay in drilling.

These results are similar to the observation of Verhulst et al. (2010) who reported that zero tillage led to lower initial growth than inversion tillage practices. Laufer & Koch (2017) also report that seedling emergence tended to be earlier and more uniform, and crop canopy tended to be higher, under intensive and minimum tillage compared to strip tillage.

### 6.4.4 Blackgrass

Blackgrass infestation was a critical issue in Top Furze (clay field) when drilled to wheat. As referred by Moss (2013), blackgrass is favoured by water retentive soils, so tends to be more of a problem on heavier clay or silt rather than on lighter sandy soils. In addition, as Godwin (2014) pointed out, good drainage is a prerequisite to ensure the soil environment is less hospitable to blackgrass. Hence, in the present study blackgrass infestation was an issue at the bottom part of the field (Figure 6.4) where water ponding was apparent and due to poor drainage. Moisture content, as monitored at the start of the cropping seasons, was 3% and 7% greater in Top Furze than Snagsborough for year 1 and 3 respectively.

Because of the high level of variation, there was no consistent treatment effect on blackgrass densities in year 1 or 3. During the three years of the experiment, the proportion of the area affected by blackgrass in Top Furze doubled (Table 6.8). Nonetheless, it worth mentioning that there seem to be some evidence of higher soil moisture contents to result in higher blackgrass head counts. For instance in year 3 the Farm system had the greatest soil moisture at 0-50 mm ($p>0.05$) depth and a significantly higher soil moisture at 150-200 mm. This ties in well with the blackgrass issue in Farm system plots which had the highest head counts value and the greatest increase between year 1 and 3.

Although the effects were not significant, the Väderstad treatment had the lowest proportional area affected in 2015-16 and the greatest increase occurred (as mentioned above) with the Farm system. The above findings are consistent with those of Fone (2013) who reported that the second pass of non-inversion tillage systems brought lumps - and blackgrass seeds - to the surface. Likewise Godwin (2014) underlined that direct drilled plots had better overall blackgrass control than two pass tillage systems.

In Top Furze when wheat was planted in 2015, the Sumo DTS was drilled 10 days later than the other treatments (Table 6.1). Moss & Lutman (2013) has indicated a 30% reduction in blackgrass with delayed drilling and Colbach et al. (2010) have also reported that the later the last tillage operation, the more weed seeds are to germinate and thus are killed by the tillage. The area and the proportional area affected, was not noticeably lower for the Sumo DTS in year 3. Although the increase of the number of heads between year 1 and 3 did not significantly vary between treatments, the increase in the Sumo DTS treatment was +98 m$^{-2}$ while the increase in the other treatments ranged from +156 to +348 m$^{-2}$ (Table 6.7).

### 6.4.5 Crop yield

Blackgrass infested areas and headlands led to lower crop yields than other parts of the field, leading to a skewed yield distribution. Yield reduction in areas close to headlands could be attributed to compaction caused by greater use of those areas by farm machinery, or damage caused from rabbits and rodents from field edges.

The coefficient of variation in Top Furze (18-29%) was substantially higher than in Snagsborough (8-20%). This was due to the reason of its clay soil texture class which is a less forgiving soil in terms of water logging as compared to Snagsborough field (clay loam). As a consequence blackgrass infestation became a big issue in season 3 causing great variation.

Yields as shown in Table 6.18 were above the UK means for all three cropping seasons (Gardiner, 2015). The wheat resulted in almost double the level of dry matter production than the oilseed rape (Table 6.17). The harvest index for wheat (0.41) was also greater than that (0.30) for oilseed rape. One reason for the lower harvest index of the oilseed rape (expressed on a weight basis) is that oilseed has a higher energy content (21.0 MJ kg$^{-1}$) than wheat grain (13.3 MJ kg$^{-1}$) (Burgess et al. 2012). In fact expressed on an energy basis the harvested yield of 4.6 t ha$^{-1}$ of the oilseed rape (97 GJ ha$^{-1}$) is about two-thirds of the energy in 11.0 t ha$^{-1}$ of wheat grain (146 GJ ha$^{-1}$).

Wheat production in Snagsborough was as good as in Top Furze in season 1. There is sometimes a presumption that wheat grows well on clay (Purcel, 2015), but it grows as well on clay loam as the present study showed. Oilseed rape showed relative consistent yields and this may be attributed to same seed rates in each season. As already discussed the low wheat yield in Top Furze in 2015-16 is due to increased blackgrass infestation, an effect which was not addressed by a higher seed rate for the wheat (Table 6.2).

Table 6.18. Mean yields (t ha$^{-1}$) for both fields within a complete rotation

| | | 2013-2014 | 2014-2015 | 2015-2016 |
|---|---|---|---|---|
| Snagsborough | Crop | Oilseed rape | Wheat | Oilseed rape |
| | Yield | 4.61 | 11.29 | 4.20 |
| | S.E | (0.01) | (0.02) | (0.01) |
| Top Furze | Crop | Wheat | Oilseed rape | Wheat |
| | Yield | 11.05 | 4.57 | 9.09 |
| | S.E. | (0.05) | (0.02) | (0.05) |

The only significant ($p<0.05$) treatment effect on yield occurred in Snagsborough in 2015-16 when the oilseed rape yield in the Sumo DTS treatment was lower than the others. This can be attributed to the late drilling, the resulting lower plant density and NDVI. At a less rigorous level of significance ($p=0.15$), in Snagsborough the Farm system resulted in a higher wheat yield than the Claydon in 2014-15 (Table 6.10) and in Top Furze the Mzuri and Väderstad resulted in a higher wheat yield than the Farm system in 2013-14 (Table 6.13). Mzuri and Väderstad also resulted in a higher oilseed rape yield than the Claydon in Top Furze in 2014-15 (Table 6.14). In Snagsborough, the Farm system was in the top two treatments each season with 3-8% yield advantage over the average. In Top Furze the highest yields in each season occurred with the Mzuri or Väderstad resulting in a 3-8% and 2-4% yield benefit over the average respectively. A possible reason for the higher ranking of the Väderstad and Mzuri in Top Furze, is that the Väderstad and Mzuri showed a greater increase in the total organic carbon ($p<0.05$) between year 1 and 3 than the Farm system and Sumo DTS. In Snagsborough, although there was not a significant difference between treatments, the Farm system also showed the highest level of total organic carbon within both years (section 5.3.4). This might be attributed to the reason that in Snagsborough the single-pass Farm system drilled oilseed rape twice (over three years) which mixed less the surface soil layer than, the two-pass Farm system in wheat which involved the Sumo Trio plus a power harrow drill.

## 6.5 Conclusions

- The Väderstad tillage treatment, which had the shallowest and narrowest level of disturbance, left the greatest amount of crop residue.
- The Väderstad treatment, everything else being equal, tended to lead to lower rates of plant establishment than the other treatments. This could be explained by its higher surface bulk densities in September 2014 and 2015, as well its greatest penetration resistance in the majority of cases in the top 50 mm of soil.
- In the clay loam soil in 2015, delaying the drilling of the oilseed rape with the Sumo DTS from 8 September to 18 September was associated with lower seedling establishment, lower NDVI, and lower yields than the other treatments. Although some of this effect may be due to late drilling, the use of the Mzuri at the same late drilling date did not result in such low plant densities and the final yield was similar to other treatments. However the same delay for the Sumo DTS in 2015 in Top Furze

resulted in similar ($p>0.05$) NDVI, plant densities and yields to the rest of the treatments. This suggests that either Sumo DTS performs better in heavier than lighter soils, or there was a human error introduced (i.e. metering system fault, seeds dropped too deep) while drilling Snagsborough in year 3.

- In both fields, yields were reduced by headlands. Removing the headland effect increased yields by 2.5 to 4.5%.
- In the clay field, blackgrass infestation was a confounding factor on yield with the level of infestation increasing from 8% of the area in 2013-2014 to 16% in 2015-16. Excluding headland and blackgrass areas in 2015-16 increased the calculated wheat yield by 6.5% from 7.80 t $ha^{-1}$ to 9.09 t $ha^{-1}$.
- In the clay loam soil, although the mean yield was not significantly higher than other treatments, the Farm system gave the highest yield. This may be associated with its highest (but not significant) percentage of total organic carbon within year 1 and 3 (when the TOC was monitored). In addition, its plant densities were significant higher in year 3, while its penetration readings were the lowest and also greater reduced ($p<0.05$) at 150-200 mm after the tillage operation in years 2 and 3. In addition in the top 50 mm in year 2, the Farm system had the lowest ($p>0.05$) penetration readings. The above would contribute to easier root elongation through the soil, which could lead to the highest NDVI and plant densities within the last year. However all treatments did not overcome the critical values of bulk density (>1.47 Mg $m^{-3}$) and penetration resistance (2MPa), that restrict root growth, during the course of the experiment.
- In the clay soil, although not significant, higher yields were achieved by Mzuri and Väderstad. These treatments showed a significantly greater increase in soil organic carbon in the clay field (Top Furze) in the top 50 mm. In addition, they were the top two treatments with the highest numbers of earthworms in years 1 and 3 in Top Furze.
- Harvest index for wheat was lower than oilseed rape, but this is compensated by the higher energy content of oilseed rape.

# 7 FINANCIAL ANALYSIS

The objective of this chapter is to determine the relative financial benefits of contrasting conservation tillage systems for wheat and oilseed rape production in the UK.

## 7.1 Introduction

Graves et al. (2005) provide a framework to determine the most appropriate models for undertaking financial and economic analyses. It also provides a useful method for developing bio-economic models. The purpose of developing the financial model in this thesis was to undertake research (Table 7.1). The remaining part of the introduction describes some of the other key aspects of the financial modelling.

Table 7.1. Criteria for the financial model used in this chapter, based on framework described by Graves et al. (2005)

| Characteristic | Criteria for the economic model. The model should be able: | |
|---|---|---|
| Background | 1.1 | To operate in English |
| | 1.2 | To be used as a research tool |
| Systems modelled | 2.1 | To model different cultivation methods |
| | 2.2 | To model oilseed rape and wheat in a two-phase rotation |
| Objectives of economic analysis | 3.1 | To use a common conceptual framework of farm economics including net margins |
| | 3.2 | To account for the effect of time on the value of money by discounting |
| | 3.3 | To compare the profitability of the systems. Discounted future benefits and costs of each system should be aggregated and a net present value, infinite net present value, and equivalent annual value calculated. |
| | 3.5 | To examine the sensitivity of each system to changes in input values |
| Viewpoint of analysis | 4.1 | To simulate the view-point at a micro-economic scale, from the perspective of a single farmer. |
| Spatial scale | 5.1 | To operate at a one-hectare scale |
| Temporal scale | 6.1 | To use a yearly time-step |
| | 6.2 | To assume a rotation of 10 years |
| Generation and use of biophysical data | 7.1 | To use biophysical data from the thesis research |
| Platform and interface | 8.1 | To be a spreadsheet ‘workbook” model, using an available and inexpensive modelling platform |
| Inputs and outputs | 9.1 | To primarily produce tabular outputs |

**The objective of the economic analysis** was to compare the five tillage treatments in each field on the basis of net margins using discounting to account for the effect of time on the value of money. This requires an understanding of revenues, costs, gross and net margins, depreciation, discounting, benefit: cost ratios, and returns on investment. These are considered in turn.

**Revenues** on an arable farm can be derived from farm income, sales of capital items and other farm-related cash sources. This can include crop revenue (i.e. the product of the value of grain per ton and the yield per hectare) and grants such as basic farm payments. The revenue ($R$; units: £ $t^{-1}$) is the product of the crop yield achieved ($Y$; units: t $ha^{-1}$) and the marketable price of the crop per tonne ($G$; units: £ $t^{-1}$) (Equation 7.1).

$$R = Y \times G \qquad \text{Eq. (7.1)}$$

**Costs** (units: £ $ha^{-1}$) on an arable farm can be split into variable and fixed costs. Variable costs, such as the cost of seed, fertilizer, and sprays can be directly related to individual crops (Moran, 2009). Fixed costs can be further divided into non-assignable and assignable costs. Assignable fixed-costs include the cost of machinery and labour. Non-assignable fixed costs include costs that are likely to be incurred irrespective of the cropping system (Nix, 2015) e.g. insurance and the cost of grain stores and buildings.

**Gross margin** (units: £ $ha^{-1}$) is defined as the value of revenues minus variable costs. It is usually expressed on a per hectare basis. In analyses where the cost of labour and machinery is important then it can be useful to calculate a **net margin** (units: £ $ha^{-1}$) determined as the revenue ($R$; units: £ $ha^{-1}$) minus variable costs ($V$; units: £ $ha^{-1}$), and the assignable fixed costs of labour and machinery ($A$; units: £ $ha^{-1}$) (Equation 7.2). A similar approach when comparing arable and forestry systems has previously been used by Graves et al. (2011).

$$\text{Net margin} = R - V - A \qquad \text{Eq. (7.2)}$$

**Depreciation** is an approach to describe the loss in value of capital items, such as machinery, over time due to wear, obsolescence and age (Lazarus, 2008). There are different ways to do this. Straight-line annual depreciation is calculated by subtracting the trade-in value of the machine from the new cost and dividing the difference by the number of years between purchase and trade-in (Equation 7.3). The trade-in value or salvage value is the estimated value of the machine at the time of trade-in (Molenhuis, 2001). The rate of depreciation is the reciprocal of the estimated useful life of an asset. Thus, for example, given the useful life of an asset is 5 years, the depreciation charged will be 1/5 = 20%.

$$Depreciation = \frac{(Cost\ of\ an\ asset - Salvage\ value)}{Useful\ life\ of\ asset\ in\ years} \qquad \text{Eq. (7.3)}$$

**Discounting** as HM Treasury (2011) explains, is a technique used to compare costs and benefits that occur in different time periods. It is based on the principle that, generally, people prefer to receive goods and services now rather than later which is known as 'time preference'. The current equivalent monetary value of a cost or benefit that will be received in the future is called net present or discounted value (Equation 7.4) where: *NPV* is the Net Present Value (£ $ha^{-1}$), *F* is the future value of cost or benefit in monetary terms (£ $ha^{-1}$), *r* is the rate of discount, and *n* is the year under consideration.

$$NPV = \frac{F}{(1+r)^{n-1}} \qquad \text{Eq. (7.4)}$$

The **return on investment** (ROI) evaluates the efficiency of the investment (the tillage treatment in particular). Return on investment measures the amount of return on an investment relative to the investment's cost. To calculate ROI, the benefit (or return) of an investment is divided by the cost of the investment, and the result is expressed as a percentage or a ratio (Equation 7.5) (Investopedia, 2016).

$$Return\ on\ investment = \frac{(Revenue - total\ costs)}{Total\ costs} \qquad \text{Eq. (7.5)}$$

**Benefit-cost ratio**: The benefit-cost ratio (BCR) is an indicator, used in the formal discipline of cost-benefit analysis that attempts to summarize the overall value for money of a project. The BCR is calculated by dividing the total discounted value of the benefits by the total discounted value of the costs (Investopedia 2016).

In terms of **viewpoints and choice of scales** (Table 7.1), the primary objective was to undertake the assessment from the perspective of an individual commercial arable farmer. The choice of spatial scale for analysis was assumed to be per hectare. The choice of temporal scale was a resolution of one year and to consider the financial effect over a period of 10 years, which was considered to be close to the lifetime of a piece of tillage equipment. The primary source of data was identified as the biophysical data established in the earlier chapters of this thesis. The platform chosen for analysis was a Microsoft Excel spreadsheet because of its wide availability.

## 7.2 Methodology

The methodology describes the systems modelled, the assumptions regarding yields and prices, and the assumptions regarding costs.

### 7.2.1 Systems modelled

The analysis seeks to model the effect of four one pass non-inversion tillage treatments in a wheat-oilseed rape arable rotation, relative to a baseline system (Farm system) which uses one pass (a Sumo Trio) when drilling oilseed rape and two passes (a Sumo Trio cultivator and a Kuhn HR seed drill) when drilling wheat. The treatments varied in terms of the depth of soil working (Table 7.2).

Table 7.2. Depth of the first and second pass (where applicable) for the tillage treatments

| Treatment | Depth of first pass (mm) | Depth of second pass (mm) |
|---|---:|---:|
| Sumo Trio followed by Kuhn HR 4002 | 200 | 100 |
| Sumo DTS | 177 | - |
| Mzuri Pro-Til 3T | 150 | - |
| Claydon Hybrid | 150 | - |
| Väderstad Seed Hawk | 25 | - |
| Väderstad Rapid 400 S | 25 | - |

The Sumo Trio, Kuhn HR and Claydon Hybrid were mounted treatments, and Mzuri, Sumo DTS and Väderstads were trailed treatments. Mounted refers to treatments that are bolted or clamped to a tractor; trailed refers to treatments drawn behind a tractor. The varieties of wheat and oilseed rape, and the timing of drilling varied from year to year (Table 7.3).

The seed rates within each crop and treatment were the same and not variable. As described in Chapter 3, the oilseed rape drilling in 2014 took place in August which was particularly wet (monthly rainfall = 99 mm), compared to September in 2013 (39 mm) and 2015 (47 mm) which were relatively dry. The oilseed rape harvest in 2015 was carried out two weeks later in the season than in 2014. Regarding the mean climatic values for the whole cropping seasons, 2014 was the wetter and warmer year with a mean rainfall of 58 mm and a mean temperature of 11.2°C compared to 2013 and 2015 (50 mm, 9.2°C & 44 mm, 10.5°C respectively).

Table 7.3. The variety of oilseed and wheat and the timing of drilling each year

| Season | Crop | Variety | Time of drilling | Seed rate (seeds m$^{-2}$) |
|---|---|---|---|---|
| 2013-14 | Oilseed | Rhino | 5 Sept 2013 | 50 |
| | Wheat | Relay | 23 Sept & 1 Oct 2013 | 300 |
| 2014-15 | Oilseed | Harper | 28 Aug 2014 | 50 |
| | Wheat | Leeds | 29 Sept 2014 | 300 |
| 2015-16 | Oilseed | Extrovert | 8 - 18 Sept 2015 | 50 |
| | Wheat | Reflection | 5 - 23 Oct 2015 | 375 |

### 7.2.2 Assumptions regarding grain prices, yields, and revenue

Prices received for wheat and oilseed rape varied substantially from year to year. In the UK, prices generally increased from a low point in 2004 to a peak in 2007, followed by a decrease before rising again in 2010-2012 (Figure 7.1). From 2012 to 2016, grain prices declined back to their level in 2009. Some of this change is associated with global growth and is associated with price changes in other global commodities such as oil.

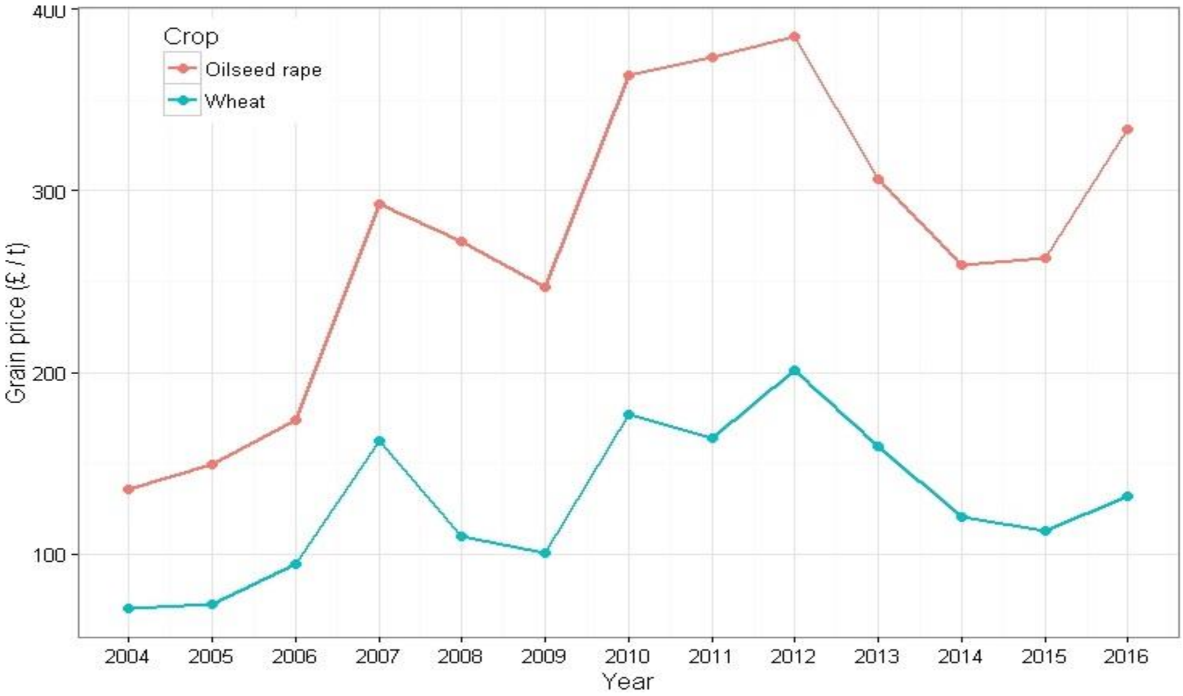


Figure 7.1. Wheat and oilseed rape grain prices in East Anglia from 2004 to 2016 (after: AHDB cereals)

Grain yields of winter wheat and oilseed rape for each of five tillage treatments in 2013-14, 2014-15 and 2015-16 were above UK average yields in each year (Table 7.4, Table 7.5) (Defra, 2015). Although the statistical analysis showed that there was no significant ($p > 0.05$) effect of treatment on grain yield, the financial analysis was carried out using the mean "corrected yields" measured in the field.

The variability in wheat yields was greatest in Top Furze, where the soil was more clayey and where there was a heavy blackgrass infestation. The corrected yields, as mentioned in Chapter 6, were the yields obtained after removing any confounding factor.

If the analysis had assumed that the price of wheat and oilseed rape changed from year to year, this would have confounded the treatment effects on predicted revenue. Hence for the purpose of this analysis, a fixed value of £285 and £120 $t^{-1}$ was selected for the oilseed rape and wheat respectively (Table 7.4, Table 7.5).

Table 7.4. Yield and revenue for each tillage treatment in Snagsborough[a]

| Treatment | 2013-14 Oilseed | | 2014-15 Wheat | | 2015-16 Oilseed | |
|---|---|---|---|---|---|---|
| | Yield ($t\ ha^{-1}$) | Revenue (£ $ha^{-1}$) | Yield ($t\ ha^{-1}$) | Revenue (£ $ha^{-1}$) | Yield ($t\ ha^{-1}$) | Revenue (£ $ha^{-1}$) |
| Farm system | 4.74 | 1,351 | 11.65 | 1,398 | 4.54 | 1,294 |
| Claydon | 4.38 | 1,248 | 11.02 | 1,322 | 4.48 | 1,277 |
| Mzuri | 4.74 | 1,351 | 11.12 | 1,334 | 4.14 | 1,180 |
| Sumo DTS | 4.81 | 1,371 | 11.40 | 1,368 | 3.43 | 978 |
| Väderstad | 4.38 | 1,248 | 11.27 | 1,352 | 4.43 | 1,263 |

[a]: Value of 285 and 120 £ $t^{-1}$ was selected for the oilseed rape and wheat respectively
Väderstad was replaced by Horsch in 2015-16

Table 7.5. Yield and revenue for each tillage treatment in Top Furze[a]

| Treatment | 2013-14 Wheat | | 2014-15 Oilseed | | 2015-16 Wheat | |
|---|---|---|---|---|---|---|
| | Yield ($t\ ha^{-1}$) | Revenue (£ $ha^{-1}$) | Yield ($t\ ha^{-1}$) | Revenue (£ $ha^{-1}$) | Yield ($t\ ha^{-1}$) | Revenue (£ $ha^{-1}$) |
| Farm system | 10.47 | 1,256 | 4.55 | 1,297 | 9.18 | 1,102 |
| Claydon | 11.02 | 1,322 | 4.30 | 1,226 | 8.71 | 1,045 |
| Mzuri | 11.39 | 1,367 | 4.94 | 1,408 | 9.51 | 1,141 |
| Sumo DTS | 11.01 | 1,321 | 4.33 | 1,234 | 8.80 | 1,056 |
| Väderstad | 11.38 | 1,366 | 4.77 | 1,359 | 9.26 | 1,111 |

[a]: Value of 285 and 120 £ $t^{-1}$ was selected for the oilseed rape and wheat respectively
Väderstad was replaced by Horsch in 2014-15

### 7.2.3 Assumptions regarding costs

The costs were calculated using the data from this thesis and the treatments' economic performance was estimated over a time span of 10 years. The prices for the labour costs, cost of diesel and the total percentage loss of capital were obtained from Nix (2015) and were kept the same for the 10 years in order to standardize and simplify calculations (Table 7.6).

Table 7.6. Assumptions for labour and diesel costs (from Nix 2015)

| Labour cost (£ $hr^{-1}$) | Cost of diesel (£ $l^{-1}$) |
|---|---|
| 10 | 0.4 |

#### *7.2.3.1 Variable costs*

It was assumed that the cost of seed was the same for each treatment. It was also assumed that the treatments received the same fertilizer applications. The level of agrochemical applications such as insecticide spraying was against flea beetle and herbicide application against weeds and blackgrass in particular was also assumed to be uniform.

#### *7.2.3.2 Common treatment and labour costs*

The machinery costs can be spilt into those common and specific to each treatment. The common treatment costs include the sprayers, trailers and combine harvester. The common treatment costs were assumed to be the same for all treatments.

#### *7.2.3.3 Treatment specific and labour costs*

The treatment specific machinery costs relate to the tillage and drilling equipment and the associated tractor. The costs associated with the tillage systems were i) their depreciation (determined from the purchase cost), ii) the fuel requirements, and iii) labour costs.

#### *7.2.3.4 Tillage treatments depreciation costs*

Treatments purchase price was obtained from manufacturers (Table 7.7), and their straight line depreciation was calculated from Equation 7.3. The first stage was to determine the capital costs of the treatments. The discount rate (r) is used to convert all costs and benefits to ‘present values’. As reported by HM Treasury (2011) discount rate for government is 3.5% while Quiggin (1997) reports that most plausible values of discount rates are in the range from 3 to 5 per cent. For the purposes of this analysis a discount rate of 4% was used; marginally above the UK Government rate. For the oilseed rape, the default (base-line) Farm system comprised the 3 m wide Sumo Trio (£16,995). For the wheat, the default Farm system was the Sumo Trio plus a 4 m wide Kuhn HR drill which have a combined cost of £23,995. Thus the Farm system had the lowest capital cost. In ascending order, the next cheapest system was the 3 m wide Mzuri (£49,971) followed by the 4 m wide Väderstad (£53,130). The most expensive treatments were the 4 m Sumo DTS (£68,995) and the 6 m wide Claydon (£60,000) (Table 7.7). It was assumed that the value of the tillage treatment after 10 years would be 30% of the current price (Nix, 2015). When assessing the treatments’ decrease in value over ten years per meter width, the Mzuri and Sumo DTS showed the highest decrease, followed by Vaderstad and Claydon while the lowest decrease was associated with the Farm system (Table 7.7).

Table 7.7. Tillage systems price, characteristics and their depreciation

| **Treatment** | Value when new | Value after 10 years[a] | Width | Decrease in value over 10 yr/m | Time to cover 1 hectare | Area covered | Straight line depreciation |
|---|---|---|---|---|---|---|---|
| | (£) | (£) | (m) | (£) | (hr $ha^{-1}$) | (ha) | (£ $ha^{-1}$ $a^{-1}$) |
| Sumo Trio (FS in osr)[b] | 16,995 | 5,099 | 3 | 3,965 | 0.48 | 370 | 3.2 |
| Kuhn | 7,000 | 2,100 | 4 | 1,225 | 0.25 | 384 | 1.3 |
| Total (FS in w)[c] | 23,995 | 7,199 | | | | | 4.5 |
| Claydon | 60,000 | 18,000 | 6 | 7,000 | 0.17 | 1,056 | 4.0 |
| Mzuri | 49,971 | 14,991 | 3 | 11,660 | 0.42 | 422 | 8.3 |
| Sumo DTS | 62,995 | 18,889 | 4 | 11,026 | 0.28 | 634 | 7.0 |
| Väderstad Rapid | 53,130 | 15,939 | 4 | 9,297 | 0.34 | 510 | 7.3 |

The time period considered in each case was 10 years

[a] Cultivation equipment is assumed to be worth 30% of the initial value after 10 years (Nix, 2015)

[b]: FS: Farm system; osr: Oilseed rape; w:Wheat

The second stage was to express the capital cost on a per area basis. This requires an understanding of the time needed to plant a known size plot (Table 7.7) expressed in hours per hectare. The calculated depreciation cost of the tillage treatment on a per area basis ranged from £4.0 $ha^{-1}$ $a^{-1}$ for the Claydon to £8.3 $ha^{-1}$ $a^{-1}$ for Mzuri to drill both wheat and oilseed rape (Table 7.7). The Farm system for drilling wheat combines the cost of the Sumo Trio (£3.2 $ha^{-1}$ $a^{-1}$) with the Kuhn seed drill (£1.3 $ha^{-1}$ $a^{-1}$) resulting in an annual cost of £4.5 $ha^{-1}$ $a^{-1}$ (Table 7.7). Likewise the hectares planted per hour, and the costs attributed to fuel requirements per hectare and the tractor's loss of value in wheat, will include both the Sumo Trio and Kuhn costs. Table 7.8 illustrates some real-time collected data at the field.

Table 7.8. Acquired information about the tillage treatments based on field measurements

| Treatment | Weather | Working depth (mm) | Block | Field | Area ($m^2$) | Working time (s) | Turning time (s) | Total time (sec) | Slippage (%) | Mean fuel (l $ha^{-1}$) | Work rate (ha $h^{-1}$) | Area time $^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sumo Trio | Dry | 200 | 4 | Snagsborough | 2573 | 375 | 17 | 426 | 2.2 | 17.0 | 2.47 | 0.16 |
| Sumo Trio | Dry | 200 | 3 | Snagsborough | 2390 | 372 | 22 | 438 | 2.2 | 17.0 | 2.31 | 0.18 |
| Sumo Trio | Dry | 200 | 2 | Snagsborough | 1361 | 315 | 19 | 372 | 1.1 | 17.0 | 1.56 | 0.27 |
| Kuhn | Wet | 100 | 4 | Top Furze | 2496 | 229 | 25 | 279 | 3.0 | 15.2 | 3.93 | 0.11 |
| Claydon | Dry | 150 | 4 | Snagsborough | 2589 | 155 | 27 | 182 | 2.1 | 9.0 | 6.02 | 0.07 |
| Claydon | Dry | 150 | 2 | Snagsborough | 2409 | 136 | 23 | 159 | 2.1 | 9.0 | 6.39 | 0.06 |
| Claydon | Dry | 150 | 3 | Snagsborough | 2471 | 138 | 20 | 158 | 2.1 | 9.0 | 6.44 | 0.06 |
| Claydon | Wet | 127 | 4 | Top Furze | 2473 | 148 | 21 | 169 | 2.1 | 9.0 | 6.03 | 0.07 |
| Claydon | Wet | 127 | 3 | Top Furze | 2127 | 137 | 22 | 159 | 2.1 | 9.0 | 5.60 | 0.07 |
| Mzuri | Wet | 177 | 3 | Snagsborough | 2459 | 323 | 30 | 413 | 3.0 | 8.0 | 2.74 | 0.17 |
| Mzuri | Wet | 177 | 2 | Snagsborough | 1368 | 207 | 34 | 309 | 3.0 | 8.0 | 2.38 | 0.22 |
| Mzuri | Wet | 150 | 1 | Top Furze | 2132 | 331 | 22 | 397 | 3.5 | 8.0 | 2.32 | 0.18 |
| Mzuri | Wet | 150 | 2 | Top Furze | 2092 | 340 | 25 | 415 | 3.5 | 8.0 | 2.22 | 0.20 |
| Mzuri | Wet | 150 | 3 | Top Furze | 2314 | 338 | 34 | 440 | 3.5 | 8.0 | 2.46 | 0.19 |
| Sumo DTS | Wet | 177 | 3 | Snagsborough | 2459 | 202 | 37 | 276 | 2.5 | 17.5 | 4.39 | 0.11 |
| Sumo DTS | Wet | 177 | 2 | Snagsborough | 1369 | 121 | 40 | 201 | 2.5 | 17.5 | 4.07 | 0.14 |
| Sumo DTS | Wet | 177 | 1 | Top Furze | 2015 | 259 | 32 | 323 | 3.7 | 17.5 | 2.80 | 0.16 |
| Sumo DTS | Wet | 177 | 2 | Top Furze | 2094 | 232 | 36 | 304 | 3.7 | 17.5 | 3.25 | 0.14 |
| Rapid 400S | Wet | 25.4 | 1 | Top Furze | 1597 | 216 | 38 | 292 | 3.0 | 5.5 | 2.66 | 0.18 |
| Rapid 400S | Wet | 25.4 | 2 | Top Furze | 2101 | 235 | 40 | 315 | 3.0 | 5.5 | 3.22 | 0.15 |
| Seed Hawk | - | 25.4 | - |  | - | - | - | - | - | - | - | - |

#### *7.2.3.5 Tractor depreciation costs*

Tractors costs and their fuel requirements were obtained from the contractors and the farmers at the experimental site. The different tillage treatments were used with tractors with different power ratings. Nix (2015) refers to a loss of capital value of 75% over a ten year lifetime for traditional machines, including tractors.

Assuming an average use of 750 hours per year (Nix, 2015), a tractor with an initial value of £90,000 would be worth £22,500 after 10 years, then the depreciation would be (90,000 - 22,500)/(750 x 10) = £8.6 hr$^{-1}$. It worth mentioning that the maintenance and insurances costs were taken from Nix (2015) who distinguished them by the tractors' horsepower. The depreciation costs associated with the use of the tractors for tillage were calculated to range from £2.60-£2.90 ha$^{-1}$ for the Claydon, Mzuri, and Väderstad. The highest tractor cost was associated with the Sumo DTS treatment; by comparison the cost for repair and maintenance for the tractor associated with the Mzuri was about half that value (Table 7.9).

Table 7.9. Cost of associated tractor and depreciation over 10 years

| **Treatment** | Tractor make | Tractor power | Tractor value as new | Tractor value after 10 years$^{b}$ | Insurance$^{a}$ | Repairs and maintenance$^{a}$ | Straight line depreciation | |
|---|---|---|---|---|---|---|---|---|
| | | kWh | (£) | (£) | (£ a$^{-1}$) | (£ a$^{-1}$) | (£ hr$^{-1}$) | (£ ha$^{-1}$) |
| Farm system | JD 7830 | 153 | 90,000 | 22,500 | 1,227 | 4,091 | 9.0 | 4.3 |
| Claydon | JD 8270 R | 201 | 158,000 | 39,500 | 1,227 | 4,091 | 15.8 | 2.6 |
| Mzuri | Case Puma | 120 | 70,340 | 17,585 | 545 | 1,818 | 7.0 | 2.9 |
| Sumo DTS | JD 8345 R | 257 | 170,000 | 42,500 | 1,227 | 4,091 | 17.0 | 4.7 |
| V'stad Rapid | NH T7 | 186 | 80,000 | 20,000 | 1,227 | 4,091 | 8.0 | 2.8 |

[a]: Estimation of insurance, repairs and hours per year for 2015 adopted from Nix (2015)
In each case the time period considered was 10 years
[b]: Tractor is assumed to be worth 25% of the initial value after 10 years (Nix, 2015)
All tractors were assumed to work for 750 hours per year
The production years were 2013 for the Farm System and Mzuri, 2014 for the Claydon and Sumo DTS, and 2012 for the Väderstad Rapid
JD = John Deere, NH = New Holland

### 7.2.3.6 Fuel requirements

The third treatment cost was the cost of diesel. The quantity of diesel required was affected by i) the treatments working depth and width, ii) whether it was mounted or trailed, having an impact on their work rate (area covered in unit time) and iii) the resulted traction efficiency of the tractor when using its particular treatment (drill).

The controlled conditions experiments presented in Chapter 4 demonstrated that deeper working implements demand more fuel. Transportability in the field could also affect the time needed to drill the seeds. Mounted treatments result in less dead times (i.e. while turning at the headlands) than trailed treatments. And finally ineffective traction could mean loss of energy in slippage which translates in more diesel requirements for the tractors. To obtain the fuel results in £ $l^{-1}$, the column with fuel usage in l $ha^{-1}$ was multiplied by the cost of fuel (£0.4 $l^{-1}$).

The Farm system (Sumo Trio + Kuhn) in wheat resulted in £12.9 $ha^{-1}$ cost of fuel for tillage. In oilseed rape where only the Sumo Trio was used, the fuel cost was £6.8 $ha^{-1}$. Claydon and Mzuri which worked at the same depth (150 mm) resulted in around the same fuel usage (£3.0 and £3.2 $ha^{-1}$ respectively). Sumo DTS worked at 177 mm resulted in £7.0 $ha^{-1}$ diesel consumption and finally Väderstad (the shallowest treatment) used £2.2 diesel per hectare (Table 7.10).

Table 7.10. Cost of associated use of fuel

| **Treatment** | Fuel usage | | | | | | |
|---|---|---|---|---|---|---|---|
| Farm system | (kW $hr^{-1}$) | (l $hr^{-1}$) | (l $kWh^{-1}$) | (l $ha^{-1}$) | (ha $kWh^{-1}$) | (kWh $ha^{-1}$) | (£ $ha^{-1}$) |
| Sumo Trio | 153 | 35.7 | 0.23 | 17 | 0.013 | 77 | 12.9 |
| Kuhn | 153 | 61.0 | 0.39 | 15 | 0.026 | 38 | 6.8 |
| Claydon | 201 | 45.0 | 0.22 | 8 | 0.030 | 34 | 3.0 |
| Mzuri | 120 | 19.2 | 0.16 | 8 | 0.020 | 50 | 3.2 |
| Sumo DTS | 257 | 63.0 | 0.25 | 18 | 0.014 | 71 | 7.0 |
| Väderstad | 186 | 15.9 | 0.09 | 5 | 0.016 | 63 | 2.2 |

### 7.2.3.7 Labour costs

The labour costs per treatment were derived from the time required to drill a hectare, namely the work rate multiplied by the labour cost usually charged for the completion of the drilling operation. The work rate, excluding turning times, depended on the speed of the operation, the width of the equipment and whether the tillage equipment was mounted or trailed. As it was assumed that each treatment was operating at the same speed of 9 kilometers per hour, only the two latter factors influenced the work rate.

The Farm system in oilseed rape comprised the mounted 3 m wide Sumo Trio, and in wheat it also included the mounted 4 m Kuhn. The two arrangements needed an average of 0.48 and 0.25 hours (29 and 15 min) to drill a hectare respectively. The mounted Claydon (6 m) needed 0.17 hours (10 min); the trailed Sumo DTS (4 m) required 0.27 hours (16 min); the trailed Mzuri (3 m) required 0.41 hours (25 min) and the trailed Väderstad (4 m) required 0.34 hours (20 min). Table 7.11 describes the aggregate costs for the Farm system including labour, equipment in terms of tractor and tillage treatment cost, fuel, tillage and drilling costs all expressed in £ per hectare.

Table 7.11. The aggregate costs for cultivation (machinery, fuel and labour) and other machinery for the Farm system

| Crop | Drilling equipment | Time | Labour | Tractor | Fuel | Total tillage and drilling | Other machinery and labour | Machinery, labour and fuel |
|---|---|---|---|---|---|---|---|---|
| | (£ ha$^{-1}$) | (hr ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) |
| Wheat | 4.49 | 0.73 | 7.3 | 6.54 | 12.9 | 31 | 88 | **119** |
| Oilseed rape | 3.22 | 0.48 | 4.8 | 4.29 | 6.80 | 19 | 88 | **107** |

## 7.3 Results

### 7.3.1 Calculating the net present value over a rotation

The revenues and costs described in the methodology were used to calculate the undiscounted and discounted net margin of each cultivation system over a 10 year rotation for Snagsborough field (Table 7.12 to Table 7.16). The revenue for the wheat and oilseed rape was derived from the yields (Table 7.4 and Table 7.5). The experiments duration was three years but assuming a ten year rotation the yields-revenues values after year 3, were simply repeated. The variable cost (seed, fertiliser and agrochemical costs) of the wheat and oilseed rape systems was assumed to be £498 ha$^{-1}$ and £439 ha$^{-1}$ a$^{-1}$ respectively for all the treatments within both fields.

Table 7.12. Farm system: estimated net present value over 10 years in Snagsborough (clay loam)

| Year | Crop | Revenue[a] | Total variable | Tillage labour and machinery | Other machinery | Gross margin | Undiscounted net margin | Discounted net margin |
|---|---|---|---|---|---|---|---|---|
| | | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) |
| 1 | Oilseed | 1,351 | 439 | 19.1 | 88 | 912 | 805 | 805 |
| 2 | Wheat | 1,398 | 498 | 31.2 | 88 | 900 | 781 | 751 |
| 3 | Oilseed | 1,294 | 498 | 19.1 | 88 | 855 | 748 | 691 |
| 4 | Wheat | 1,398 | 439 | 31.2 | 88 | 900 | 781 | 694 |
| 5 | Oilseed | 1,351 | 498 | 19.1 | 88 | 912 | 805 | 688 |
| 6 | Wheat | 1,398 | 439 | 31.2 | 88 | 900 | 781 | 642 |
| 7 | Oilseed | 1,294 | 498 | 19.1 | 88 | 855 | 748 | 591 |
| 8 | Wheat | 1,398 | 439 | 31.2 | 88 | 900 | 781 | 593 |
| 9 | Oilseed | 1,351 | 498 | 19.1 | 88 | 912 | 805 | 588 |
| 10 | Wheat | 1,398 | 439 | 31.2 | 88 | 900 | 781 | 549 |
| Total | | 13,631 | 4,685 | 251 | 880 | 8,946 | 7,814 | 6,592 |
| Average | | 1,363 | 468 | 25.1 | 88 | 895 | 781 | 659 |

[a]: the oilseed rape yield alternates for the two values measured; the wheat revenue is fixed.

In subsequent tables, the column "Total variable" is omitted. Likewise, the "Other machinery" column will be also omitted because its value of £88 ha$^{-1}$ a$^{-1}$, which included costs of combining, was similar for all treatments. The undiscounted net margin in the first year in oilseed rape was £54 ha$^{-1}$ a$^{-1}$ higher than in the next year's wheat (two pass treatment) and £114 ha$^{-1}$ a$^{-1}$ higher than the oilseed rape in year 3 (Table 7.12). The Farm system resulted in an average discounted net margin of £659 ha$^{-1}$ a$^{-1}$ over the 10 years. Tillage and drilling costs (which included labour and machinery costs) were £31.2 and £19.0 $ha^{-1}$ $a^{-1}$ for wheat and oilseed rape respectively. The Claydon treatment (Table 7.13) was predicted to result in a lower undiscounted net margin (£723 $ha^{-1}$ $a^{-1}$) than the Farm system (£781 $ha^{-1}$ $a^{-1}$) (Table 7.12). This is primarily a result of the predicted lower revenue (£1291 $ha^{-1}$ $a^{-1}$) than the Farm system (£1363 $ha^{-1}$ $a^{-1}$), although this was partially offset by lower tillage and drilling costs (£11 $ha^{-1}$ $a^{-1}$) than the Farm system (£25 $ha^{-1}$ $a^{-1}$). The lower cost of the Claydon system was due to its lower work rate (hr $ha^{-1}$) and that it worked 50 mm shallower.

Table 7.13. Claydon: estimated net present value over 10 years in Snagsborough (clay loam)

| Year | Crop | Revenue | Tillage labour and machinery | Gross margin | Undiscounted net margin | Discounted net margin |
|---|---|---|---|---|---|---|
| | | (£ $ha^{-1}$) | (£ $ha^{-1}$) | (£ $ha^{-1}$) | (£ $ha^{-1}$) | (£ $ha^{-1}$) |
| 1 | Oilseed | 1,248 | 11.2 | 809 | 710 | 710 |
| 2 | Wheat | 1,322 | 11.2 | 824 | 725 | 697 |
| 3 | Oilseed | 1,277 | 11.2 | 838 | 739 | 683 |
| 4 | Wheat | 1,322 | 11.2 | 824 | 725 | 645 |
| 5 | Oilseed | 1,248 | 11.2 | 809 | 710 | 607 |
| 6 | Wheat | 1,322 | 11.2 | 824 | 725 | 596 |
| 7 | Oilseed | 1,277 | 11.2 | 838 | 739 | 584 |
| 8 | Wheat | 1,322 | 11.2 | 824 | 725 | 551 |
| 9 | Oilseed | 1,248 | 11.2 | 809 | 710 | 519 |
| 10 | Wheat | 1,322 | 11.2 | 824 | 725 | 509 |
| Total | | 12,911 | 112.0 | 8226 | 7,233 | 6,101 |
| Average | | 1,291 | 11.2 | 823 | 723 | 610 |

In Snagsborough, the Mzuri (Table 7.14) average annual undiscounted net margin (£733 $ha^{-1}$) was £47 $ha^{-1}$ lower than the Farm system (£781 $ha^{-1}$ $a^{-1}$), and £10 $ha^{-1}$ higher than the Claydon (£723 $ha^{-1}$). The primary reason was the predicted increase in the mean annual revenue to £1,308 $ha^{-1}$ compared to £1,291 $ha^{-1}$ for the Claydon; a benefit of £17 $ha^{-1}$. The cost for tillage and drilling with the Mzuri (£18 $ha^{-1}$ $a^{-1}$) was broadly similar to the Farm system (£25 $ha^{-1}$ $a^{-1}$), and the yield advantage more than offset the reduced cost with the Claydon (£11 $ha^{-1}$ $a^{-1}$).

Table 7.14. Mzuri: estimated net present value over 10 years in Snagsborough (clay loam)

| Year | Crop | Revenue | Tillage labour and machinery | Gross margin | Undiscounted net margin | Discounted net margin |
|---|---|---|---|---|---|---|
| | | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) |
| 1 | Oilseed | 1,351 | 18.5 | 912 | 805 | 805 |
| 2 | Wheat | 1,334 | 18.5 | 836 | 730 | 702 |
| 3 | Oilseed | 1,180 | 18.5 | 741 | 634 | 586 |
| 4 | Wheat | 1,334 | 18.5 | 836 | 730 | 649 |
| 5 | Oilseed | 1,351 | 18.5 | 912 | 805 | 688 |
| 6 | Wheat | 1,334 | 18.5 | 836 | 730 | 600 |
| 7 | Oilseed | 1,180 | 18.5 | 741 | 634 | 501 |
| 8 | Wheat | 1,334 | 18.5 | 836 | 730 | 555 |
| 9 | Oilseed | 1,351 | 18.5 | 912 | 805 | 588 |
| 10 | Wheat | 1,334 | 18.5 | 836 | 730 | 513 |
| Total | | 13,085 | 185.0 | 8,400 | 7,334 | 6,188 |
| Average | | 1,308 | 18.5 | 840 | 733 | 619 |

The Sumo DTS treatment (Table 7.15) resulted in a similar average annual undiscounted net margin of £713 ha$^{-1}$ as the Claydon (£723 ha$^{-1}$), but it was £68 and £20 lower than that of the Farm system and Mzuri respectively (£781-733 ha$^{-1}$). The Sumo DTS was predicted to result in also the same revenue with the Claydon (£1291 ha$^{-1}$) and £17 lower from Mzuri, but this was more than offset by an increase of the annual tillage cost to £21 ha$^{-1}$ as compared to £18.5 ha$^{-1}$ and £11 ha$^{-1}$ for Mzuri and Claydon respectively.

Lastly the Väderstad system (Table 7.16) was predicted to give an average annual undiscounted net margin (£731 ha$^{-1}$) similar to the Mzuri (£733 ha$^{-1}$) but £18 and £8 higher than the Sumo DTS and Claydon respectively (£713-723 ha$^{-1}$). This is primarily a result of the high predicted annual revenue (£1,303 ha$^{-1}$) which was similar to Mzuri (£1,308 ha$^{-1}$) and greater than the Sumo DTS and Claydon (£1,291 ha$^{-1}$). The annual Väderstad tillage cost (£15.6 ha$^{-1}$) is greater than the Claydon (£11 ha$^{-1}$) but less than the other systems (£18-25 ha$^{-1}$).

Table 7.15. Sumo DTS: estimated net present value over 10 years in Snagsborough (clay loam)

| Year | Crop | Revenue | Tillage labour and machinery | Gross margin | Undiscounted net margin | Discounted net margin |
|---|---|---|---|---|---|---|
| | | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) |
| 1 | Oilseed | 1,371 | 21.4 | 932 | 822 | 822 |
| 2 | Wheat | 1,368 | 21.4 | 870 | 761 | 731 |
| 3 | Oilseed | 978 | 21.4 | 539 | 429 | 397 |
| 4 | Wheat | 1,368 | 21.4 | 870 | 761 | 676 |
| 5 | Oilseed | 1,371 | 21.4 | 932 | 822 | 703 |
| 6 | Wheat | 1,368 | 21.4 | 870 | 761 | 625 |
| 7 | Oilseed | 978 | 21.4 | 539 | 429 | 339 |
| 8 | Wheat | 1,368 | 21.4 | 870 | 761 | 578 |
| 9 | Oilseed | 1,371 | 21.4 | 932 | 822 | 601 |
| 10 | Wheat | 1,368 | 21.4 | 870 | 761 | 534 |
| Total | | 12,908 | 214.0 | 8,223 | 7,128 | 6,007 |
| Average | | 1,291 | 21.4 | 822 | 713 | 600 |

Table 7.16. Väderstad system: estimated net present value over 10 years in Snagsborough (clay loam)

| Year | Crop | Revenue | Tillage labour and machinery | Gross margin | Undiscounted net margin | Discounted net margin |
|---|---|---|---|---|---|---|
| | | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) |
| 1 | Oilseed | 1,248 | 15.6 | 809 | 706 | 706 |
| 2 | Wheat | 1,352 | 15.6 | 854 | 751 | 722 |
| 3 | Oilseed | 1,263 | 15.6 | 824 | 720 | 666 |
| 4 | Wheat | 1,352 | 15.6 | 854 | 751 | 667 |
| 5 | Oilseed | 1,248 | 15.6 | 809 | 706 | 603 |
| 6 | Wheat | 1,352 | 15.6 | 854 | 751 | 617 |
| 7 | Oilseed | 1,263 | 15.6 | 824 | 720 | 569 |
| 8 | Wheat | 1,352 | 15.6 | 854 | 751 | 570 |
| 9 | Oilseed | 1,248 | 15.6 | 809 | 706 | 516 |
| 10 | Wheat | 1,352 | 15.6 | 854 | 751 | 527 |
| Total | | 13,032 | 156.0 | 8,347 | 7,310 | 6,163 |
| Average | | 1,303 | 15.6 | 834 | 731 | 616 |

Table 7.17 presents the economic results for all treatments within Top Furze over the 10 year time (the detailed results per treatment for the Top Furze is presented in Appendix D). The Mzuri and Väderstad had the highest discounted net margins of £646

and £623 ha$^{-1}$ a$^{-1}$ respectively, whilst the Farm system, Claydon and Sumo DTS had similar values of £546-560 ha$^{-1}$ a$^{-1}$. In general, the total costs were lowest for the Claydon (£99 ha$^{-1}$ a$^{-1}$) followed in ascending order by Väderstad, Mzuri, Sumo DTS and Farm system (£104, 106, 110 and 113 ha$^{-1}$ a$^{-1}$ respectively) ( Table 7.18).

Table 7.17 Estimated net present value over 10 years in Top Furze for the five systems (clay)

| Year | Revenue | Tillage labour and machinery | Gross margin | Undiscounted net margin | Discounted net margin |
|---|---|---|---|---|---|
| | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) |
| Farm system | 12,456 | 251.3 | 7,771 | 6,640 | 5,587 |
| Claydon | 12,185 | 112.7 | 7,500 | 6,507 | 5,484 |
| Mzuri | 13,422 | 185.8 | 8,737 | 7,671 | 6,456 |
| Sumo DTS | 12,246 | 214.6 | 7,561 | 6,466 | 5,450 |
| Väderstad | 13,116 | 156.8 | 8,431 | 7,394 | 6,226 |

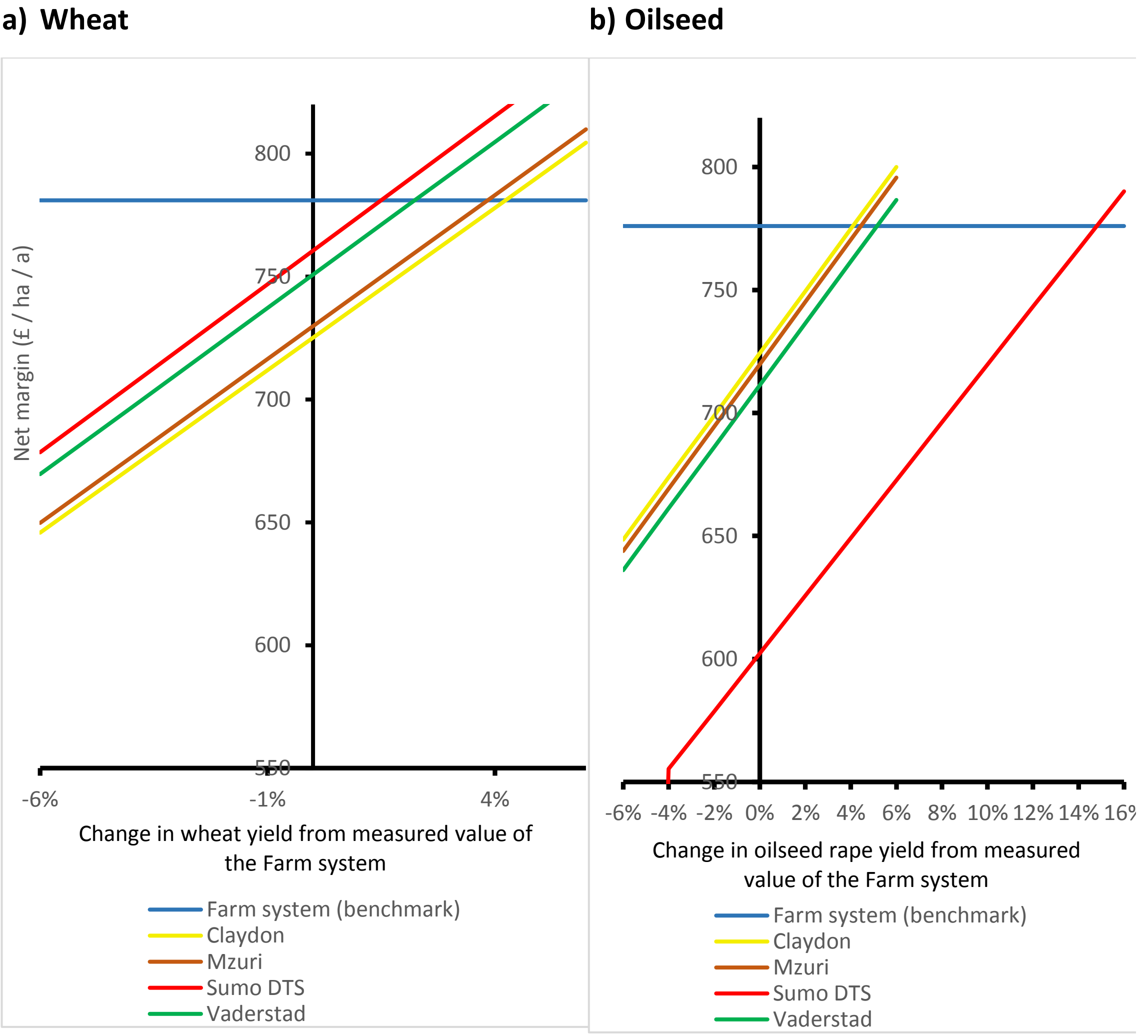
In Snagsborough, the net margins across the five systems were more consistent (£600-£659 ha$^{-1}$ a$^{-1}$). The lowest predicted discounted net margin value was obtained with the Sumo DTS (£600 ha$^{-1}$ a$^{-1}$) and the highest with the Farm system (£659 ha$^{-1}$ a$^{-1}$). The Claydon, Mzuri and Väderstad showed similar values of £610-619 ha$^{-1}$ a$^{-1}$. The high net margin with the Farm system was primarily a result of a higher predicted revenue.

Table 7.18. Summary table of the average total costs, revenue and discounted net margin per year for each treatment as separated by the experimental fields

| Treatment | | Snagsborough | | Top Furze | |
|---|---|---|---|---|---|
| | Total costs | Revenue | Discounted net margin | Revenue | Discounted net margin |
| | (£ ha$^{-1}$ a$^{-1}$) | (£ ha$^{-1}$ a$^{-1}$) | (£ ha$^{-1}$ a$^{-1}$) | (£ ha$^{-1}$ a$^{-1}$) | (£ ha$^{-1}$ a$^{-1}$) |
| Farm system | 113.3 | 1,363 | 659 | 1,246 | 560 |
| Claydon | 99.3 | 1,291 | 610 | 1,218 | 548 |
| Mzuri | 106.5 | 1,308 | 619 | 1,342 | 646 |
| Sumo DTS | 109.5 | 1,291 | 600 | 1,225 | 545 |
| Väderstad | 103.7 | 1,303 | 616 | 1,312 | 623 |

### 7.3.2 Sensitivity analysis

Using the Farm system as a benchmark, a sensitivity analysis was used to determine the extent of yield change required to achieve the same net margin as the Farm system for each crop and field. In Snagsborough and for wheat for instance, the Farm system gave an average annual £781 ha$^{-1}$ net margin based on a 11.65 t ha$^{-1}$ yield. All treatments needed extra yield to result in the same net margin to the Farm system. For the wheat crop, the Sumo DTS needed a 1.7%, the Väderstad 2.3% and the Mzuri and Claydon needed 4% higher yield of that they already produced in order to result in the same annual net margin of £781 ha$^{-1}$ (Figure 7.2a).



**a) Wheat** **b) Oilseed**

Figure 7.2. Effect of proportional changes in the a) wheat yield and b) the oilseed rape yield in Snagsborough on the net margin of the Claydon, Mzuri, Sumo DTS and Väderstad net margin relative to that obtained for the Farm system

Within Snagsborough for the oilseed rape, the benchmark net margin was £776 $ha^{-1}$ $a^{-1}$ based on a 4.64 t $ha^{-1}$ yield. Hence, Claydon, Mzuri and Väderstad would require 2-4% higher yield than that actually achieved while the Sumo DTS needed a 14% higher yield than that achieved to achieve the net margin of the Farm system (Figure 7.2b). The higher yield needed by the Sumo DTS is due to the low oilseed rape yield in year 3 due to late drilling. In Top Furze for the oilseed rape, the Sumo DTS and Claydon required a 4% higher yield than that achieved to provide the same annual net margin as the Farm system (£750 $ha^{-1}$) which gave a yield of 4.55 t $ha^{-1}$. By contrast, Mzuri and Väderstad would give the same net margin as the Farm system if they produced around 8% and 5% less yield (i.e. 0.3 t $ha^{-1}$ less) than they actually did (Figure 7.3b).

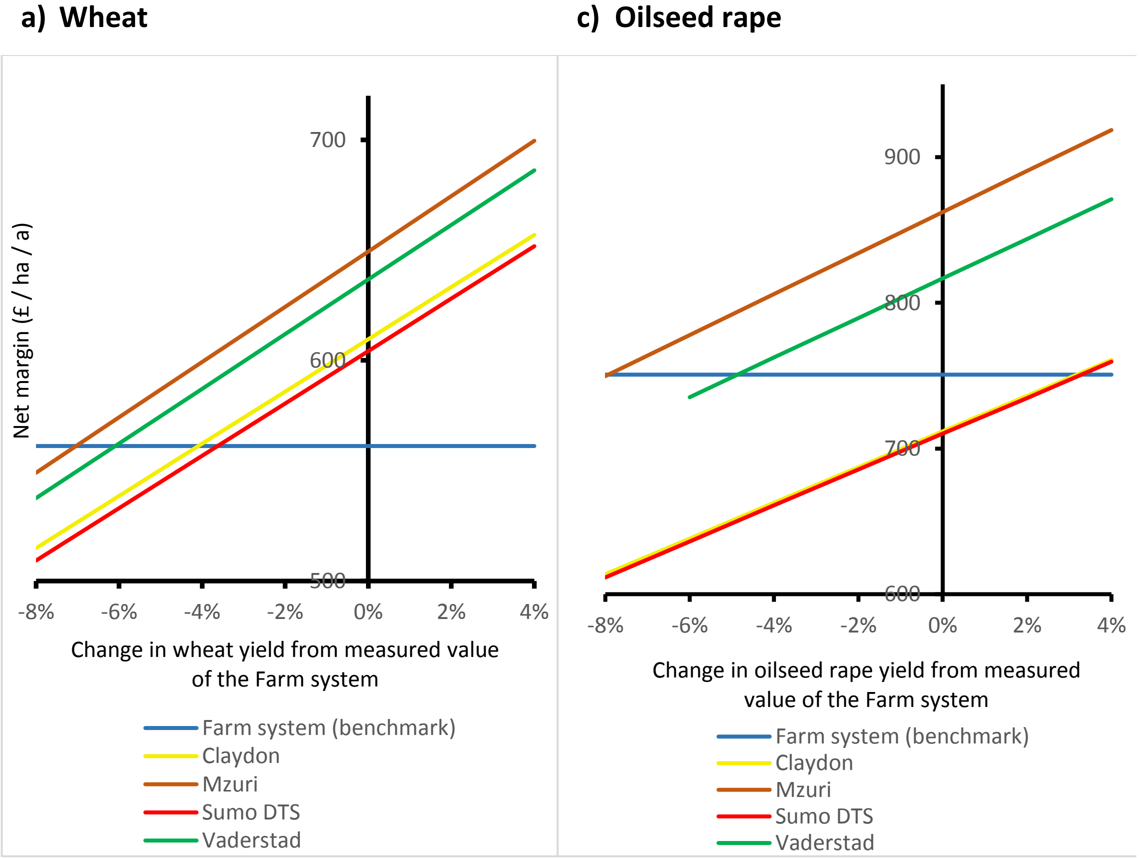


Figure 7.3. Effect of proportional changes in the a) wheat yield and b) the oilseed rape yield in Top Furze on the net margin of the Claydon, Mzuri, Sumo DTS and Väderstad net margin relative to that obtained for the Farm system

Finally in Top Furze with wheat, the Farm system resulted in the lowest net annual margin of £561 $ha^{-1}$ with an average yield of 9.82 t $ha^{-1}$ while the other four treatments achieved higher net margins because of the higher (not significantly yields). Sumo DTS and Claydon yielded 4% more while Mzuri and Väderstad 6 and 7% respectively (Figure 7.3a). The poor net margin of Farm system was a function of the yield variability due to the blackgrass infestation. Both its total blackgrass infested area and total heads per meter square were higher ($p>0.05$) and the increase between year 1 and 3 was also greater than the rest of the treatments (Section 6.3.4).

## 7.4 Discussion

The most profitable tillage system for the farmer is determined by the balance between the effect on yield and the effect on costs.

### 7.4.1 Effect of yield

As mentioned in Chapter 6 it was difficult to establish a significant ($p<0.05$) tillage treatment effect on yield because of the high co-efficient of variation (Table 7.19). The only significant ($p<0.05$) effect was in year 3 in Snagsborough, where the Sumo DTS (which was drilled 10 days later than the other treatments with the exception of the Mzuri) resulted in a lower oilseed rape yield.

Table 7.19. Summary table of the coefficient of variation of yield for both fields per year

| | **Snagsborough** | | |
|---|---|---|---|
| | Oilseed rape | Wheat | Oilseed rape |
| **cvar (%)** | 19.4 | 8.5 | 20.1 |
| | **Top Furze** | | |
| | Wheat | Oilseed rape | Wheat |
| **cvar (%)** | 18.4 | 29.0 | 21.1 |

The presented financial analysis used the mean corrected yields actually measured in each field, even though they did not differ statistically. Hence in Snagsborough, where the Farm system gave the highest yield, it also gave the highest discounted net margin (£659 ha$^{-1}$ a$^{-1}$). On the other hand in Top Furze, the top two discounted net margins were attributed to Mzuri and Väderstad (£646-623 ha$^{-1}$ a$^{-1}$) which also gave the highest yield. In accordance with the present results, Guedes Filho et al. (2010) also reported yield variation which was attributed to factors such as weather, weeds and soil when studied long term no tillage in Sao Paolo. In addition, Smith et al. (2007) and Palosuo et al. (2011) also reported that climate change may accentuate future crop yield variability. The financial analysis highlights the key role of the yield assumptions in determining the benefits of a treatment. For example, a wheat yield advantage of only 0.2 t $ha^{-1}$ of one treatment over another could increase the revenue by £2,400 per year on a 100 ha farm (wheat price £120 $t^{-1}$).

Although the high yield variability (i.e. blackgrass or within-field soil variability) do not allow significant ANOVA results, farmers are highly likely to choose the treatment that result even in the smallest yield advantage as this would have a direct impact on their final net margin per cropping season.

### 7.4.2 Effect on costs

Total costs as mentioned before included i) machinery and labour costs for combining, ii) for spraying and for iii) tillage and drilling. The first two costs were similar for all treatments. Thus the tillage and drilling costs were the only differing costs between the treatments. They included: a) treatment depreciation in £ per annum (loss in value over time), b) labour costs (£ $a^{-1}$), calculated by the product of the work rate (hr $ha^{-1}$) and the assumed labour cost of 10 £ $hr^{-1}$, c) tractor depreciation costs and d) fuel costs.

The lowest total costs assigned to Claydon are related to its greater working width influencing its work rate (0.17 hr $ha^{-1}$) resulting in lower labour costs than the other treatments (Table 7.23). The use of the Farm system with wheat was more expensive because it required two operations. The Väderstad needed the least amount of fuel per hectare (£2.2), the Mzuri and Claydon had similar fuel requirements (£3.0-3.2 $ha^{-1}$) while Sumo DTS and Farm system had the highest fuel costs (£7.0 and 9.8 $ha^{-1}$ respectively).

Table 7.20. Summary table of the average costs associated with tillage and drilling per hectare alongside the treatments work rate.

| Treatment | Time required (hr ha$^{-1}$) | Costs for tillage and drilling (£ ha$^{-1}$ a$^{-1}$) | | | | |
|---|---|---|---|---|---|---|
| | | Treatment depreciation | Labour | Tractor depreciation | Fuel | Total |
| Farm system | w: 0.73<br>osr: 0.48 | w: 4.5<br>osr: 3.2 | w: 7.3<br>osr: 4.8 | w: 6.5<br>osr: 4.3 | w: 12.9<br>osr: 6.8 | 31.2<br>19.1 |
| Claydon | 0.17 | 3.9 | 1.6 | 2.6 | 3.0 | 11.1 |
| Mzuri | 0.42 | 8.3 | 4.1 | 2.9 | 3.2 | 18.5 |
| Sumo DTS | 0.28 | 7.0 | 2.7 | 4.7 | 7.0 | 21.4 |
| Väderstad | 0.34 | 7.3 | 3.4 | 2.7 | 2.2 | 15.6 |

w: wheat; osr: oilseed rape

The results also highlight the importance of selecting the right tractor. As Table 7.9 indicates, Mzuri and Claydon have similar rates of tractor depreciation per hectare per annum (£2.6-2.9 ha$^{-1}$) even though the Claydon has double the working width of Mzuri (Table 7.7). Depreciation was similar because, the Mzuri required more time to drill a hectare (lower width) but the tractor used with the Mzuri costed half the price of the tractor used with the Claydon (Table 7.9).

### 7.4.3 Sensitivity to soil characteristics

The treatments show different rankings in terms of profitability between the two fields. Within the heavier field (Top Furze) Väderstad and Mzuri were top ranked in terms of yields than the lighter Snagsborough field. As reported in Chapter 6, these treatments were associated with higher levels of total organic carbon, and greater values of water stable aggregates when compared to i) the other treatments within the same field and ii) the organic carbon and aggregation values in Snagsborough. These responses should have enhanced the yields with the Väderstad and Mzuri and hence the higher net margin in Top Furze (Table 7.18). On the other hand, within Snagsborough the Farm system yielded highest (even not statistically significant). In Snagsborough, the Farm system was associated with a greater organic carbon percentage, lower penetrometer readings that may have helped roots elongate, and higher plant densities (Chapter 6). These allowed the Farm system to achieve a higher net margin on the lighter soil in Snagsborough (Table 7.18).

### 7.4.4 Benefit-cost ratio (BCR)

As mentioned in section 7.1 the gross margin-cost ratio or the benefit-cost ratio is an indicator of cost-benefit analysis that attempts to summarize the overall value for money of a project. It is calculated by dividing the total discounted value of the benefits by the total value of the costs. Table 7.21 and 7.22 summarise the financial results, namely the revenue, the total costs, the benefit-cost ratio and the return on investment in combination with the treatments' working depth and width for both fields.

Table 7.21. Gross margin: labour and machinery cost ratio and predicted return on investment of the five treatments in Snagsborough over 10 years

| Treatment | Width (m) | Depth (mm) | Gross margin (£ $ha^{-1}$ $a^{-1}$) | Total costs (£ $ha^{-1}$ $a^{-1}$) | Benefit : cost ratio | Return on investment (%) |
|---|---|---|---|---|---|---|
| Farm system | 3 mt | 200 | 891 | 113.3 | 7.86: 1 | 4.80 |
| Claydon | 6 mt | 150 | 822 | 99.3 | 8.28: 1 | 5.15 |
| Mzuri | 3 tr | 150 | 840 | 106.5 | 7.88: 1 | 4.80 |
| Sumo DTS | 4 tr | 177 | 822 | 109.5 | 7.50: 1 | 4.47 |
| Väderstad | 4 tr | 25 | 835 | 103.7 | 8.05: 1 | 4.94 |

*Values for economics refer to average values per cropping season; mt = mounted, tr = trailed

Table 7.22. Gross margin: labour and machinery cost ratio and predicted return on investment of the five treatments in Top Furze over 10 years

| Treatment | Width (m) | Depth (mm) | Gross margin (£ $ha^{-1}$ $a^{-1}$) | Total costs (£ $ha^{-1}$ $a^{-1}$) | Benefit : costs ratio | Return on investment (%) |
|---|---|---|---|---|---|---|
| Farm system | 3 mt | 200 | 777 | 113.3 | 6.85: 1 | 4.28 |
| Claydon | 6 mt | 150 | 750 | 99.3 | 7.55: 1 | 4.50 |
| Mzuri | 3 tr | 150 | 874 | 106.5 | 8.20: 1 | 5.07 |
| Sumo DTS | 4 tr | 177 | 756 | 109.5 | 6.90: 1 | 3.98 |
| Väderstad | 4 tr | 25 | 843 | 103.7 | 8.13: 1 | 5.00 |

*Values for economics refer to average values per cropping season; mt = mounted, tr = trailed

The ranking of the treatments in terms of the benefit: cost ratio is generally similar to that for the net margin. For example the Mzuri and Väderstad rank highest in Top Furze giving around £8.20 benefit for every £1 spent. However the lower cost associated with Claydon means that in Snagborough it actually generates the highest benefit to cost ratio giving £8.28 for every £1 spend on costs.

### 7.4.5 Guidance on equipment selection

The above analysis highlights that the most profitable system depends on the assumptions made. The choice of the most appropriate system is likely to be based on both financial and non-financial factors. The premise of this thesis is that a farmer should consider what is the most profitable and the most environmentally beneficial system. The economic competitiveness of the project's treatments described above, showed that all the treatments resulted in positive net margins per cropping season. The effects on crop growth, yield and soil were addressed in the previous chapters. In particular, and given their purchase price, working width and depth, Väderstad and Mzuri performed well in terms of net margins (£ $ha^{-1}$) for both fields.

Table 7.23 attempts to highlight the key advantage and disadvantage of each treatment in terms of their financial performance. In brief, the Sumo Trio and Sumo DTS consumed the most fuel, the Sumo DTS was the most expensive, and the Sumo Trio was the cheapest treatment to purchase. A key advantage of the Claydon was its high working rate due to its wide working width, which had the lowest costs for tillage and drilling. The Claydon and Sumo Trio were mounted treatments and as a result they reduced the turning times at the borders of the fields. Finally, low fuel use was noted for Väderstad and Mzuri which is in line with the results of Chapter 4.

Table 7.23. Strengths and weaknesses of the tillage treatments applied

| **Treatment** | **Width (m)** | **Strengths** | **Weaknesses** |
|---|---|---|---|
| Farm system | 3 | Purchase price, turning times, depreciation | Net margin, work rate, fuel use, drilling cost |
| Claydon | 6 | Drilling cost, work rate, turning times, depreciation, fuel use | Net margin |
| Mzuri | 3 | Purchase price, net margin, drilling cost, fuel use | Depreciation, turning times |
| Sumo DTS | 4 | Work rate, Net margin | Purchase price, fuel usage |
| Väderstad | 4 | Purchase price, net margin, drilling cost, fuel use | Turning times |

### 7.4.6 Equipment choice and farm size

As described in section 7.2.3.4 it is assumed from Nix (2015) there are 22 “8 hour days” per year available to drill both oilseed rape and wheat. The above analysis was based on assumed costs per hectare where each piece of equipment was used to an “optimum” capacity of 22 days. However in practice, farm enterprises have a fixed size and hence some equipment choices may result in below-optimum use of equipment (Table 7.24).

As Morris (2006) pointed out, studies in the UK have found that work-rates are much improved under conservation tillage systems offering greater flexibility and timeliness for weather dependent operations. He also concluded that this allows for soils to be cultivated at the optimum time with regards to soil conditions that are suitable for working and thus creating a seedbed favourable for crop establishment.

Table 7.24. Width, work rate and area covered per year for each treatment

| **Treatment** | Width | Time required per hectare | Number of 8 hr days[b] | Area covered |
|---|---|---|---|---|
| | (m) | (ha hr$^{-1}$) | (days) | (ha) |
| Sumo Trio (FS in osr)[a] | 3 | 2.1 | 22 | 370 |
| Kuhn (FS in w)[a] | 4 | 4.0 | 12 | 384 |
| Claydon | 6 | 6.0 | 22 | 1,056 |
| Mzuri | 3 | 2.4 | 22 | 422 |
| Sumo DTS | 4 | 3.6 | 22 | 634 |
| Väderstad Rapid | 4 | 2.9 | 22 | 510 |

[a]: FS: Farm system; osr: Oilseed rape; w:Wheat

In practical terms and as Earl (1997) studied, depending on the weather and soil type, soils become non-workable at high moisture contents. Thus a dry start of a cropping season could lead in better timeliness as there would be less time pressure for the farmer regarding field operations like tillage. By contrast in a wet start of a season, the available soil workable days could be reduced, for example, by half compared to dry conditions. In that case, the farmer is constrained as to drill all of the area in a very limited period. For example if we assume a 700 ha farm, in a dry year where there are 45 days available to drill the 700 ha, all treatments would serve as suitable farm choice. However the Claydon would do the job quicker but would be out of use for about half the time. This would increase its cost per hectare for tillage and drilling. By contrast, in a wet autumn where there are only i.e. 18 available days to work the soil, the farmer will benefit from a system which can drill the 700 hectares in that time. In this case wider treatments like Claydon could be advantageous in order to cover as many hectares as possible in the short period of time. Although a farmer could purchase two Sumo Trios or two Mzuris to achieve the same area as one Claydon (6 m), this would require higher number of employees, and additional tractors and associated costs. Even if the purchase price of two Sumo Trios is £20,000 less than one Claydon, the extra costs mentioned above could be significant.

Better time management when drilling, can reduce costs which can lead to better economic benefits in the future. This is also in line with Townsend et al. (2016) who showed that the improved timeliness of field operations resulting from the lower labour and machinery requirements of the system, could lead to better yields in the future. Finally, in England and Wales and as reported by Rounsevell & Brignall (1994), autumn soil tillage opportunities will be improved by global warming unless precipitation increases by 15% or more. Thus, there seem to be more flexible choices in the future regarding the farm tillage and drilling equipment, however this will also depend on farm size.

## 7.5 Conclusions

It is easy to raise the question which piece of tillage equipment was most cost-effective? The answer is not so simple and comparing the above treatments with different widths the final conclusions are:

- Correct tractor selection affected the insurance and repairs-maintenance costs and depreciation costs associated with tillage. The tractor depreciation associated with tillage with the Mzuri (£7.0 hr$^{-1}$) was the lowest of the studied treatments.
- The calculated costs for tillage labour and machinery (ignoring repairs and maintenance) ranged from £11 ha$^{-1}$ a$^{-1}$ for the Claydon system to £31 ha$^{-1}$ a$^{-1}$ for the two-pass Farm system comprising the Sumo Trio and a Kuhn seed drill. The

corresponding cost for Väderstad was £15.6 $ha^{-1}$ $a^{-1}$ while Mzuri, Sumo DTS and one pass Farm system range was £18.5-21.4 $ha^{-1}$ $a^{-1}$. The above values assumed optimal use over 10 years and a diesel cost of 40 p $l^{-1}$.

- The most profitable systems were primarily associated with those providing the highest yields. Mzuri and Väderstad gave high net margins across both fields and the Farm System did well at Snagsborough. The high yields with these systems were associated with higher organic carbon values.
- When comparing in pairs of same width, at 4 m width the Väderstad performed better than the Sumo DTS because the Väderstad was cheaper, worked shallower, and needed less fuel per unit area. At 3 m width, the Mzuri generally performed better than the Farm system, although the Farm system required the lowest capital outlay.
- The widest system, the 6 m Claydon, resulted in the cheapest costs for tillage and drilling.
- The depreciation cost was affected by the width of the equipment which affected the work rate, impacting this way the area covered per cropping season.

# 8 SYNTHESIS

This chapter revisits the objectives and hypotheses introduced in Chapter 1 and synthesises how they have been addressed in the thesis. The chapter also discusses the contributions to knowledge and future work.

## 8.1 Characterisation of tillage treatments

Although it was not a stated objective, the research required a clear characterisation of the different tillage treatments. Each tillage treatment was a form of non-inversion conservation tillage. The treatments included the deep working (200 mm deep) Farm system, which involved a two pass system in wheat (Sumo Trio followed by a power harrow drill) and a one pass system in oilseed (Sumo Trio). The Claydon, Mzuri, Sumo DTS and Horsch systems were one-pass strip tillage drills. Lastly the Väderstad was a very shallow system (25 mm deep) which barely manipulated the soil surface and was the closest to a no-till system (Table 8.1).

Table 8.1. Brief description of the treatments’ configuration

| Treatment | Working depth of implement (mm) | | Type of tillage | Type of implement and geometry | | |
|---|---|---|---|---|---|---|
| | 1st Pass | 2nd Pass | | Type | Rake angle* (°) | Width (mm) |
| Farm system** | 200 | 100 | Deep | Tine | 15 | 215 |
| Claydon | 150 | - | Strip tillage | Tine | 70 | 20 |
| Mzuri | 150 | - | Strip tillage | Tine | 45 | 100 |
| Sumo DTS | 177 | - | Strip tillage | Tine | - | 15 |
| Horsch | 100 | - | Strip tillage | Tine | - | 20 |
| Väderstad | 25 | - | Shallow | Disc | - | - |

*Sumo DTS was not tested in the controlled conditions experiment;

** Farm system in oilseed rape involved only the Sumo Trio

As mentioned in Chapter 2 the Horsch replaced the Väderstad Seed Hawk in oilseed rape in Top Furze in year 2 and in Snagsborough in year 3. The drill was designed with a similar philosophy as the Väderstad Seed Hawk but it worked 75 mm deeper; it was not tested in the controlled soil bin facility. As shown in Figure 8.1 and reported in Chapter 4, the area of soil disturbed by the principal working implement tended to lead to a higher draught requirement. The average draught requirements per implement(s) ranged from 0.1 kN for the Väderstad Rapid to 1.32 kN for the Claydon. Mzuri had a horizontal draught of 0.98 kN while the Farm system (Sumo Trio) resulted in a horizontal draught of 1.24 kN (Figure 8.1). Although the Claydon worked 50 mm shallower than the Sumo Trio, it had a higher energy requirement. This can be attributed to the Claydon tine having a higher rake angle and higher aspect ratio which meant that it worked below a "critical depth". The Farm system, in Figure 8.1a represents the Sumo Trio while in Figure 8.1b the Sumo Trio plus the Kuhn power harrow drill.

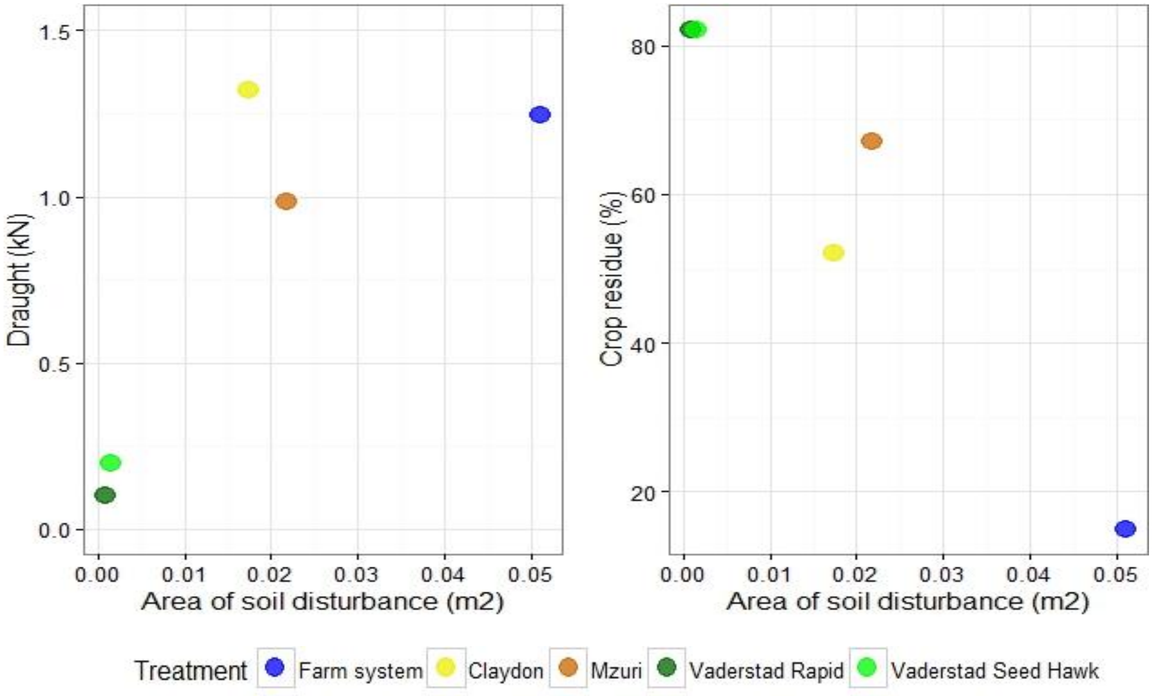


Figure 8.1. a) Draught requirement of the main working implement per treatment and b) proportion of soil covered with crop residue as a function of the cross sectional area of disturbed soil. (The Väderstad Seed Hawk is assumed to leave a similar crop residue as the Rapid)

In the field, there was a consistent low value of crop residue (15%) left by the two pass Farm system and the crop residue was greatest (80%) with the shallow Väderstad treatment. In summary the shallow treatments required less energy, disturbed less soil and left the greatest amount of surface crop residue (Figure 8.1). By contrast, the two-pass Farm system demanded higher energy, increased the cross section of disturbed soil, and led to the lowest amount of crop residue. The energy requirements, soil disturbance and crop residue for the deep single pass treatments were intermediate.

### 8.1.1 Objective 1

The first objective was “to determine the effect of the conservation tillage systems on soil condition”. The five conservation tillage systems had different effects on the i) physical, ii) chemical and iii) biological properties of the soil. The associated hypothesis, introduced in Chapter 1, was that different conservation tillage systems have different effects on soil condition.

There were significant treatment effects on soil **physical properties** with the Farm system and the Väderstad generally representing the extremes. The deep and disruptive Farm system resulted in the lowest bulk density values when assessed immediately after tillage in year 2 and 3 at both depths within both fields (Table 5.2 and 5.3). However these reductions in bulk density were not apparent at the end of the cropping season: the intensive cultivation primarily resulted in a short-term decrease in bulk density. The Farm system also led to a reduction of the penetration resistance between tillage operation within both fields at the soil surface and at 150-200 mm. There were cases where Väderstad had higher penetration resistances at 0-50 mm than the two-pass Farm system immediately after tillage in wheat. In terms of the intermediate treatments, in September 2014, the Claydon resulted in the greatest penetration resistance at 150-200 mm within both fields (2.25 and 2.13 MPa), and it resulted in a greater increase in penetration resistance in the clay loam soil between August and September 2015 (+0.28 MPa). The Sumo DTS increased penetration resistance at both 0-50 mm and 150-200 mm (+0.062 and +0.412 MPa respectively). As mentioned previously, the Claydon narrow tine had a depth/width aspect ratio of 7.5:1, which suggests that it was working just below the critical depth causing the soil to fail sideways at depth (lateral) (as illustrated in the soil bin experiment). Although Sumo DTS was not tested in the soil bin, the high penetrometer readings at depth also suggests that with an aspect ratio of 11.8: 1, it was working below its critical depth. In year 1 and 2, there was no tillage treatment effect on the proportion of water stable aggregates, but in the last year Väderstad resulted in the greater value ($p < 0.05$) than the others in the clay loam field.

In terms of soil **chemical properties** there were treatment effects on total organic carbon but not on available nitrogen. Each of the conservation tillage treatments increased total organic carbon over time (range 0.03-0.41 t C $ha^{-1}$). In the surface layer (0-50 mm) of the clay soil over the three years, the Mzuri and Väderstad showed a greater ($p < 0.05$) organic carbon increase than Sumo DTS and Farm system. By contrast, the Farm system showed the highest organic carbon content in the clay loam field in 2014 and 2016 ($p = 0.40$). In the clay loam field, there was only one season of wheat and hence the mixing by the Kuhn seed drill within the Farm system will have been less than in the clay field where there were two seasons of wheat.

In terms of the soil **biological properties**, Väderstad resulted in significantly greater microbial biomass carbon than the Claydon and Farm system in year 1 and ranked highest for the rest of the years within both fields ($p=0.15$-$0.30$). Over the 3-year experiment, the Väderstad also resulted in the greatest abundance of earthworms while Farm system (two pass system) reduced them in the wheat crop within years 1 and 3. The rest of the treatments resulted in statistically similar values. Hence, the hypothesis that the tillage treatments affected the soil physical, chemical and biological properties was supported.

### 8.1.2 Objective 2

The second objective was “to determine the effect of the conservation tillage systems on crop growth and yield”. The associated hypothesis presented in Chapter 1 was that different conservation tillage systems have different effects on crop growth and yield.

The amount of crop residue was considered in this section as it partly depends on the preceding crop growth, although it has direct effects on soil properties. The crop residue left on the soil surface immediately after tillage varied with treatment. The disruptive two-pass Farm system resulted in the lowest level of residue (15%) whereas the single pass treatments resulted in residue levels > 40%. In each year, the Väderstad left the highest residue coverage which was > 75%.

The tillage treatments affected the plant population per square metre and the Normalized Difference Vegetation Index. These values were generally greater in treatments that i) were drilled earlier than others and ii) by treatments which had the lowest soil bulk density or penetration resistance at 0-50 mm. For example the Farm system in year 3 had the greatest number of oilseed plants per meter square (44 $m^{-2}$). By contrast, the Väderstad resulted in the lowest ($p<0.05$) oilseed rape and wheat plants in year 1 and 2 respectively (20 and 220 $m^{-2}$) and the lowest NDVI in the first year in wheat. The oilseed rape crop, compared to the wheat, can show a greater ability to compensate for low plant numbers, and in the last year, the oilseed NDVI of 0.15 was similar for the Väderstad and the Farm system.

There were high co-efficients of variation in the yield levels. This was partly a result of the blackgrass infestation in the clay field and low yields near headlands. Some variation could be attributed to inaccuracies in online yield measurement on the combine, but this typically amounts to only 0.5-4% (Burks et al. 2002; Risius, 2014).

Although not significant at $p < 0.05$, the Väderstad and Mzuri gave higher ($p < 0.15$) yields than the Farm system and Claydon within the clay field. Within the clay loam field Farm system gave higher yields ($p < 0.20$-$0.25$) than the Claydon, Mzuri and Sumo DTS but similar to Väderstad. In year 3 in the clay loam soil a delay in drilling (10 days) with the Sumo DTS resulted in the lowest oilseed rape yield ($p < 0.05$), however the Mzuri which was used on the same day resulted in a similar yields to the earlier-drilled treatments. Hence the hypothesis that the five tillage treatments resulted in significant differences in crop growth and yield is supported, but apart from the date effect of the Sumo DTS, the crop yield differences were only significant at a $p = 0.15$-$0.25$ level rather than $p = 0.05$.

### 8.1.3 Objective 3

The third objective was "to determine the effect of the conservation tillage systems on energy-use efficiency and farm profitability". The associated hypothesis presented in Chapter 1 was that different conservation tillage systems have different effects on profitability and energy-use efficiency.

A detailed financial analysis was undertaken that considered the relative costs and benefits of the conservation tillage systems. Although the yields differences were not significant at $p = 0.05$, the analysis was based on the actual corrected yields recorded in the experiment. The two main determinants of the relative profitability of the five systems were therefore the assumed yield levels and the cost of the tillage. The calculated cost of the tillage treatments ranged from 11 to 31 £ $ha^{-1}$ $a^{-1}$. The work rate was influenced by the treatment width and whether they were mounted or trailed. The mounted 6 m Claydon resulted in the highest work rate (6 ha $hr^{-1}$) which reduced in turn its depreciation costs as it increased the area covered per season. In terms of net margins, Väderstad and Mzuri resulted in similar net margins of £623-646 $ha^{-1}$ within the clay field. That is in line with their higher observed yields ($p=0.15$) within the same field. Within the clay loam field the greatest yield, as mentioned above, was attributed to the Farm system which resulted in the highest annual net margin of £659 $ha^{-1}$. The shallow working Väderstad resulted in the lowest fuel usage. The controlled condition experiments (Chapter 4) also showed that the Väderstad required the lowest draught (0.1 kN) (Figure 8.1). However the appropriate configuration of the tines can also help reduce the draught requirements of deep working tines. For example, the Mzuri and Farm system (Sumo Trio), which worked above the critical depth, required less draught (0.98 and 1.24 kN per implement) than, for example, the Claydon (1.32 kN). As reported in Chapter 4, the critical depth is the working depth below which soil loosening is minimal and soil fails sideways in a lateral-like failure. By contrast, implements working above critical depth cause soil loosening in a crescent like failure (forwards and upwards).

The hypothesis that the five tillage systems resulted in different energy requirements was supported by the research. Although there were predicted differences in net margins these were not statistically tested.

### 8.1.4 Objective 4

The fourth objective was "to understand how different tillage systems affect soil condition, crop growth and yield, and farm profitability". Whereas the previous three sections considered the three items separately, this section attempts to bring them together. As presented in the Introduction (Chapter 1, Figure 1.3) there are interrelations between the parameters examined in each Chapter. The effect of the different tillage systems primarily derive from the tillage action on a single pass, i.e. a few seconds of activity per square metre, with the responses observed over the subsequent season. The effects of the tillage and drilling process are considered in terms of the impact on four key parameters of the above objectives which drive the crop production. These include the impacts on i) crop residue, soil microorganisms, and change in organic carbon, ii) soil physical factors, iii) yield and iv) costs and benefits both in terms of the clay field (Table 8.2) and the clay loam field (Table 8.3)

Table 8.2. Summary of the performance of each treatment on clay soil

| Treatment | Crop residue and carbon | | | Physical soil | | Yield | Financial | |
|---|---|---|---|---|---|---|---|---|
| | Crop residue[a] (%) | Earth-worms [b] ($m^{-2}$) | Change in TOC[c] (%) | Soil bulk density[d] ($Mg\ m^{-3}$) | Moisture Content[e] (%) | Wheat [f] ($t\ ha^{-1}$) | Annual costs[g] ($£\ ha^{-1}$) | Net margin[h] ($£\ ha^{-1}\ a^{-1}$) |
| | Figure 6.1 | Table 5.15 | Table 5.10 | Table 5.3 | Table 5.8 | Table 6.15 | Table 7.18 | Table 7.18 |
| Farm* | 15 | 75 | 0.079 | 1.090 | 34.1 | 9.18 | 113 | 560 |
| Sumo DTS | 48 | 103 | 0.102 | 1.169 | 34.2 | 8.80 | 109 | 545 |
| Claydon | 52 | 119 | 0.195 | 1.194 | 33.2 | 8.71 | 99 | 548 |
| Mzuri | 67 | 137 | 0.389 | 1.199 | 32.7 | 9.51 | 106 | 646 |
| Väderstad | 82 | 187 | 0.408 | 1.162 | 34.0 | 9.26 | 104 | 623 |

[a]: Top Furze planted to wheat in 2015; [b]: Top Furze in 2015-16
[c]: 0-50 mm from 2014 to 2016; [d]: Soil bulk density (0-50 mm) immediately after tillage in Top Furze in October 2015
[e]: Soil moisture (0-50 mm) on 24 October 2015
[f]: Corrected wheat yield in Top Furze in 2016; yields are not significantly different
[g]: Total costs associated to both fields; [h]: Mean annual net margin of wheat and oilseed in clay field over a 10 year period
*Farm system in winter wheat;

Table 8.3. Summary of the performance of each treatment on clay loam soil

| Treatment | Crop residue and carbon | | | Physical soil | | Yield | Financial | |
|---|---|---|---|---|---|---|---|---|
| | Crop[a] residue (%) | Earth-worms [b] ($m^{-2}$) | Change in TOC[c] (%) | Soil bulk density[d] ($Mg\ m^{-3}$) | Moisture content[e] (%) | Wheat[f] ($t\ ha^{-1}$) | Annual costs[g] (£ $ha^{-1}$) | Net margin[h] (£ $ha^{-1}\ a^{-1}$) |
| | Figure 6.1 | Table 5.15 | Table 5.9 | Table 5.2 | Table 5.7 | Table 6.10 | Table 7.18 | Table 7.18 |
| Farm* | 17 | 116 | 0.027 | 1.169 | 30.6 | 11.63 | 113 | 659 |
| Sumo DTS | 45 | 131 | 0.047 | 1.339 | 26.1 | 11.41 | 109 | 600 |
| Claydon | 60 | 62 | 0.061 | 1.297 | 26.6 | 11.02 | 99 | 610 |
| Mzuri | 52 | 88 | 0.084 | 1.319 | 26.1 | 11.12 | 106 | 619 |
| Väderstad | 78 | 228 | 0.105 | 1.284 | 29.7 | 11.27 | 104 | 616 |

[a]: Snagsborough planted to wheat in 2014; [b]: Snagsborough in 2014-15

[c]: Change in total organic carbon (0-50 mm) from 2014 to 2016

[d]: Soil bulk density (0-50 mm) immediately after tillage in Snagsborough in October 2014

[e]: Soil moisture (0-50 mm) on 11 October 2014

[f]: Corrected wheat yield in Snagsborough in 2015; yields are not significantly different

[g]: Total costs associated to both crops; [h]: Mean annual net margin of wheat and oilseed in clay loam over a 10 year period

*Farm system in winter wheat;

A first impact of the tillage system is the potential mixing of the residue of the previous crop residue. Within the clay field, the Farm system possessed the significant lower value of 15% in wheat (two-pass system) while the shallow working Väderstad had the significant greater percentage of above 75% within all years and both fields (Figure 6.1). Another impact of tillage is the effect on soil organisms which again is related to the crop residue values as the latter is their primary food source. The Farm system contributed in reducing the earthworms' numbers significantly when drilling the wheat (two-pass system) while Väderstad resulted in the highest values in both clay and clay loam soils. A potential effect of the increased level of residue is also that in the clay field the Väderstad, together with the Mzuri, resulted in a greater ($p<0.05$) increase in total organic carbon at 0-50 mm between year 1 and 3 (+2.80 t C $ha^{-1}$) than the Farm system and Sumo DTS (+0.56 and +0.63 t C $ha^{-1}$). However, all treatments increased their organic carbon values between the start and the end of experiment. Väderstad had the greatest microbial biomass carbon (MBC) at 0-50 mm within the clay field in year 1 ($p = 0.001$; 444 µg C g $soil^{-1}$). In addition, although not statistically significant, Väderstad was ranked highest in terms of MBC at 0-50 mm within all years and fields ($p = 0.15$-$0.35$). In year 3, Väderstad also showed significantly higher soil aggregation (51%) within the clay-loam field than the other treatments (p<0.05).

A second impact of the tillage system is on soil physical properties. The disruptive effect of the Farm system increased the porosity and decreased the bulk density of the soil at 0-50 mm and 150-200 mm. This in turn led to a reduced penetration resistance compared to the other treatments. By contrast the higher bulk density and penetration resistances obtained with the Väderstad tended to lead to lower rates of crop establishment as indicated by low plant densities and NDVI. The tillage system may also affect the moisture content in the surface layer; for example in 2014 the moisture content in the clay loam soil was higher in the Farm treatment than the Mzuri, Claydon and the Sumo DTS.

The tillage treatments also affected soil penetration resistance at depth. The Claydon and the Sumo DTS, which operated at a high depth to width ratio tend to increase penetration resistance at 150-200 mm. This is in line with the soil bin findings. Finally, soil hydraulic conductivity did not show any significant treatment effect; however the Claydon resulted in the lowest value in the clay (p=0.35) and Väderstad in the highest in the clay loam field (p=0.07).

The experiments highlighted the importance of timing in relation to tillage. The delay in tillage of the oilseed rape in year 3 with the Sumo DTS resulted in the significant lower value of plants per unit area. Although the Mzuri was also used at the same time, it did not have the same negative impact on yields.

The net effect of the differences in crop residue, soil disturbance at different depths, and soil organisms was associated with yield changes. In the clay soil, the higher increase in organic matter levels observed with the Väderstad and the Mzuri treatments were associated with higher yields (p = 0.15). Yields in the clay loam field did not result in any treatment effect but the Farm system resulted in the highest wheat yields in 2014-15 and it also showed the lowest bulk density (Table 8.3).

Blackgrass was a serious issue in the clay field and got worse with the continued use of conservation tillage, with the number of heads per metre square being higher, but not significant, for the Farm system in year 3 than year 1. Although not statistically significant, the Väderstad and Claydon blackgrass infested areas were lower in size (p = 0.40) for both years than the other treatments. The delayed drilling in Top Furze for the Sumo DTS concluded in the lowest increase in blackgrass heads among year 1 and 3, but that was also not statistically significant.

The calculated cost for tillage, labour and machinery was the lowest in Claydon while the two pass Farm system was the most costly. However the calculated net margin of the different systems was primarily determined by the yield benefits, hence the highest net margin was achieved by the Mzuri and Väderstad in the clay field and the Farm system in the clay loam field.

### 8.1.5 Objective 5

The fifth objective was “to identify how the configuration and use of cultivation and seed placement method can be optimized”.

The high values of crop residue with Väderstad was associated with an increase in earthworm numbers and total organic carbon; crop residue is the main food source of earthworms. By contrast the intensive two-pass Farm system left the lowest amount of crop residue and led to reduced earthworm numbers. An increase in soil organic carbon can act as a glue, binding soil particles strongly together resulting in turn in greater water stable aggregates. In addition earthworms play an important role in binding soil particles together due to i) the increase of soil carbon through the mineralisation they bring about and ii) their exudates which also act as a glue. Thus, all the above result in a better long-term soil structure with a well-developed porosity. By contrast, continuously using intense tillage systems (that include more than one-pass) makes it difficult to build-up soil structure.

Tillage management seeks to achieve a balance between the short-term benefits of intensive cultivation and the potential long-term benefits of low disturbance tillage (i.e. no-tillage). This interaction can be finely balanced. In the clay field, the highest yield, although not significant, was obtained with the Väderstad. It can be argued that the high surface bulk densities that could have hindered establishment were offset by its higher number of earthworms, total organic carbon and water stable aggregates. The Mzuri also resulted in an increase in soil carbon in the top 50 mm; this was also associated with a high yield. This suggests that the no-till Väderstad system could have led to improved yields in the clay field, were it not for the high blackgrass numbers that affected each of the conservation tillage systems.

By contrast in the clay loam field, where there were two crops of oilseed rape and one crop of wheat, blackgrass was not a problem. This may explain why the overall wheat yield was higher. In this situation, it was the Farm system, rather than the Väderstad, which resulted in the highest, although not significant, yield. Väderstad lower levels of plant establishment may explain its yield values in the lighter field. Although the soil organic carbon in Farm system was highest ranked (Table 5.9) ($p = 0.40$) for each individual year, the change among year 1 and 3 was greater ($p = 0.65$) for Väderstad (+0.105%) than the Farm system (+0.027%).

The net effect of the above responses were that the Mzuri and Väderstad led to the highest margins in the clay field, while the Farm system led to higher net margins in the clay loam. This was despite the 6 m wide Claydon having the lowest per hectare cost for tillage and drilling.

Arising from the analysis, some guidance can be given on how to optimise the tillage systems. The Mzuri required a lower draught than the Claydon despite working at the same depth. This was related to Mzuri's lower rake angle (45°) and wider tine (100 mm) which worked at lower aspect ratio. By contrast the Claydon, with its higher rake angle (70°) non-winged 20 mm tine, was working slightly below its critical depth demanding more energy. Likewise even though the Sumo Trio was working 50 mm deeper than the Claydon, the main working implement required 0.17 kN less draught than the Claydon in the soil bin. The Sumo Trio implement had the lowest specific resistance due to its low rake angle and high width.

## 8.2 Contributions to knowledge

This thesis has investigated the implications of five commercial conservation tillage systems on agronomic, environmental and economic performance of growing oilseed rape and wheat in rotation. The contributions are discussed in terms of their contribution to science, in terms of guidance to farmers on the strengths and weaknesses of each system, to manufacturers regarding the improvement of systems' configuration, and to government in terms of the agronomic and environmental benefits.

### 8.2.1 Contribution to science

Past studies have focused primarily on the tillage effects on i) specific soil properties, ii) crop parameters, iii) profitability or iv) a combination of two effects (e.g. soil + crop yield). However this study provides an integrated assessment of their effects on major soil properties (physical, chemical and biological), on crop growth and yield, on energy requirements, and on farm profitability.

The methodology used in the soil bin to understand the energy use, soil disturbance, and soil failure of the different systems is unique. The controlled condition experiments (Chapter 4), were carried out by using the extended octagonal ring transducer developed by Godwin (1975). The system has been used to study different designs and configuration of tillage implements and tyres, but it have not been used to study components of five commercial minimum tillage systems.

The thesis has contributed to scientific understanding as it has provided some evidence of how an increase in crop residue can lead to increased soil organic content in the surface layer and increased yields. The regression analyses in Chapter 5 describe some of the anticipated responses. These regressions suggest that a tillage system that leaves 10% more crop residue, will increase earthworms' numbers per year by 1,200 ha$^{-1}$ and carbon stocks by 0.04% (0.28 t ha$^{-1}$) within a time span of three years (section 5.4.5). Furthermore, assuming that the crop residue left on the soil surface caused an increase of the total organic carbon by 1% namely 7 t C ha$^{-1}$, this will in turn decrease soil bulk density by 0.1 Mg m$^{-3}$ and increase the soil water aggregate stability by 15% (section 5.4.6 and 5.4.10). In turn this reduction in soil bulk density and the associated increase in porosity can be expected to provide the growing crop with better access to water and air. Over time, the presence of surface residue is also expected to reduce the risk of surface runoff and erosion. This needs to be balanced with drawbacks of zero-tillage such as a lower rate of plant establishment.

### 8.2.2 Guidance to farmers

The sustainable use of conservation tillage within a winter wheat rotation requires that blackgrass is kept under control. In this experiment, blackgrass was under control within the clay loam field and the conservation tillage systems could have been continued. By contrast blackgrass was rapidly increasing in the clay soil. Hence a common practice to help control blackgrass when conservation tillage is practiced on clay soils is ploughing every 3-4 years. Farmers are highly likely to favour equipment which maximises farm profitability for a given farm size, soil type, and climatic conditions.

In the present study the most profitable systems in the clay field (Väderstad and Mzuri) seemed to also have the greatest environmental performance (in terms of soil carbon, earthworms and, in the case of the Väderstad, low energy use). In the clay loam soil, the Farm system (Sumo Trio) also looked of interest. For 400 ha of arable land, in a "typical year" it may be possible to cover the area using a single 3 m drill like the Sumo Trio and Mzuri, but if using a single drill on greater areas, then a drill of 4 to 6 m width is probably more appropriate. However, as mentioned in Section 7.4.6, the available soil workable days depend on the weather. Large equipment can give more time to the farmer to cultivate and drill and this can be particularly important in seasons when the "working window" is limited by rainfall and wet soil conditions.

### 8.2.3 Guidance to manufacturers

The thesis highlights that it is not simple to produce a single minimum tillage system that is ideal for all situations.  In the clay loam soil and with oilseed rape being the dominant crop, the highest net margin was obtained with the Farm system. It gave the highest yields ($p=0.15$), it was the cheapest tillage system, and it had lower energy requirements than the Claydon. In the clay field, the Väderstad and the Mzuri gave the highest calculated net margins. The research does provide some guidance in terms of implement configuration and design. In case of the Claydon non-winged tine (20 mm wide, 70° rake angle), the study showed that tilling too deep demanded more energy than the Sumo Trio winged tine working 50 mm deeper in heavy soils (215 mm wide, 15° rake angle). An important factor is that non-winged tines should not overcome the aspect ratio limit of 6 (where critical depth appears), below which energy is lost through soil lateral failure. In addition, the configuration and design of Mzuri, which worked at 150 mm, showed that it performed equally to the very shallow (25 mm) Väderstad.

### 8.2.4 Informing government

The aim of government for the agricultural sector is to promote the profitable production of high volumes of high quality safe food whilst enhancing the environment. To a large extent the market system is able to identify the most cost-effective way of producing food, but the market sometimes fails in that individual producers do not have to cover the cost of negative environmental externalities. In this regard, the no-tillage system deserves specific attention. The Väderstad resulted in more soil organisms, higher levels of soil carbon in the surface layer, and demanded less fossil fuel which would result in lower $CO_2$ emissions, while the increased surface residue can decrease runoff and soil erosion. In cases where there is no blackgrass infestation, such as in light well drained soils, farmers should be encouraged to switch to low disturbance tillage systems (i.e. no tillage) which they can use over numerous seasons.

## 8.3 Future work

Future work could seek to express aspects of the environmental performance of tillage systems in financial units (£ ha$^{-1}$). This would be possible by assessing the cost of any soil degradation processes as i.e. organic carbon losses, soil compaction and soil erosion.

The oilseed rape-wheat rotation was insufficient to control blackgrass infestation. Although, blackgrass is likely to remain a major problem with conservation tillage systems, farmers require to deal with it in an adaptive approach. This requires an integrated approach including insight into new herbicides in order to deal with herbicide resistance and into how cover crops may help with blackgrass weed control.

This study highlighted substantial within-field yield variability. In some cases variability within treatments was as strong as variability between treatments. Thus further research is needed, into precision technologies that will address the spatial relationship between crop yields and soil properties.

Lastly, there is more scope for research into within-field tillage implements configuration and design. For example SOYL Ltd and Cultivating solutions Ltd, have designed a “variable depth cultivator” where along with information from soil or weed maps enables the working depth of soil loosening tines to be varied on the move. This philosophy could be further developed by creating a one-pass tillage and drilling system, which at the same time would involve variable tillage depth and/or tine width on the move. Thus depending on the field, the result would include the combination of the short term advantages of deep and the long term advantages of the shallow tillage systems (no tillage).

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# Appendices

## Appendix A: Sampling points for soil texture analysis

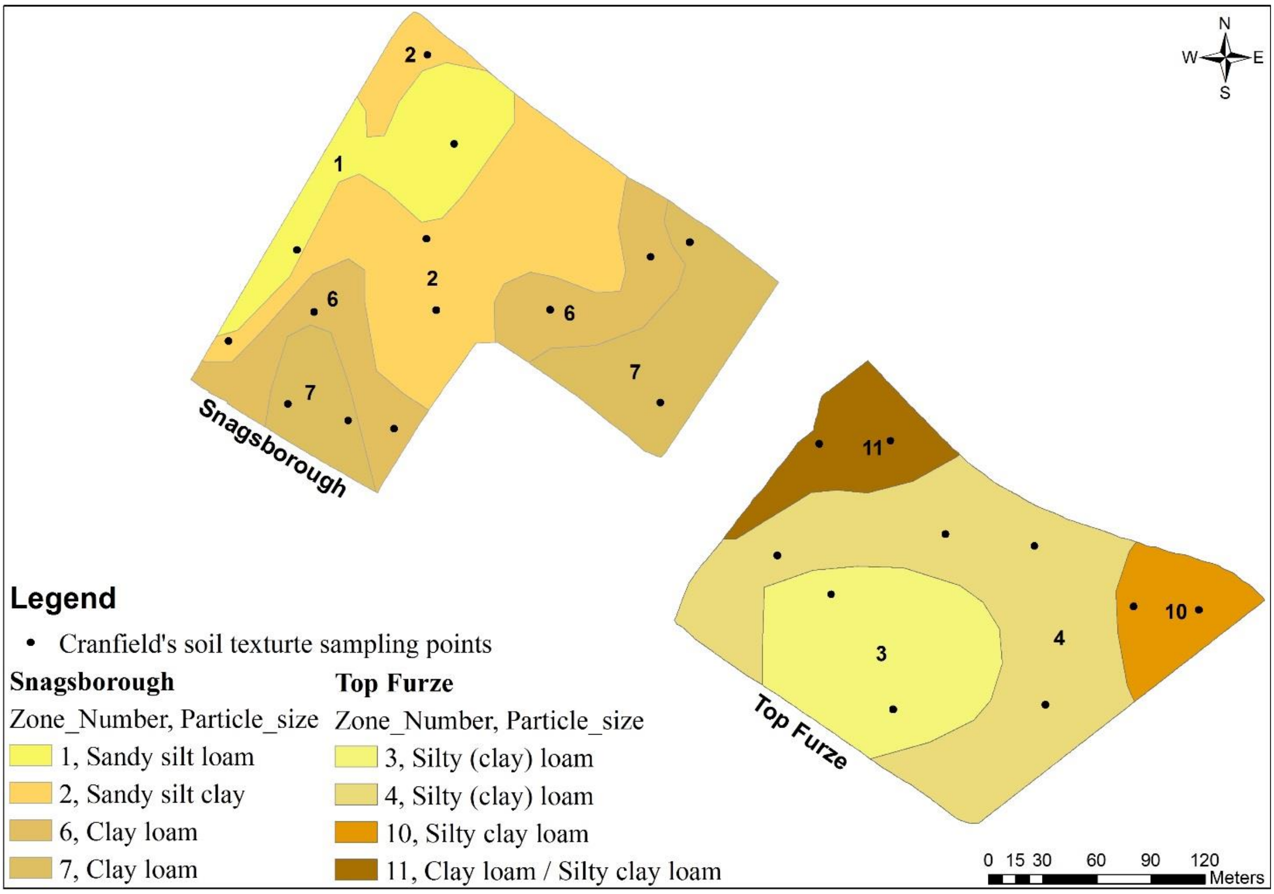


Figure A. Cranfield’s soil texture sampling points based on field zoning carried out by SOYL Ltd

## Appendix B: Testing of implement combinations

Figure 1. Väderstad Seed Hawk tests combinations

Because Väderstad Seed Hawk as shown in Figure 1 (top left picture) had low width of disturbance, the procedure of the experiments was the same as described in Chapter 4 namely to fit three experimental runs across the width of the bin without any impact from one run line to another.

Figure 2. Claydon Hybrid tests combinations

Figure 1 and 2 depict the different combinations of tests for Seed Hawk and Claydon. The Seed Hawk was tested in four (Table 1) and Claydon in two combinations respectively as described in Table 2. In the case of the Mzuri, Sumo Trio and Väderstad

Rapid, only the working tines and disc respectively were tested and there were no test combinations.

Table 1. Väderstad: Mean values for bulk density, penetration resistance and force requirements for three components of the Väderstad

| **Väderstad** | *Left part* | | *Right part* | |
|---|---|---|---|---|
| **Seeding tine** | Before run | After run | Before run | After run |
| Bulk density (Mg m$^{-3}$) | 1.34 b | 1.50 a | 1.45 ab | 1.42 ab |
| Penetration (MPa) | 1.12 ab | 1.34 a | 1.37 a | 0.85 a |
| Horizontal draught (kN) | 0.16 | | 0.20 | |
| Vertical force (kN) | 0.84 | | 0.75 | |

| **Väderstad** | *Left part* | | *Right part* | |
|---|---|---|---|---|
| **Whole unit** | Before run | After run | Before run | After run |
| Bulk density (Mg m$^{-3}$) | 1.51 a | 1.52 a | 1.55 a | 1.61 a |
| Penetration (MPa) | 1.01 a | 1.49 a | 1.32 a | 1.11 a |
| Horizontal draught (kN) | 0.16 | | 0.20 | |
| Vertical force (kN) | 0.84 | | 0.75 | |

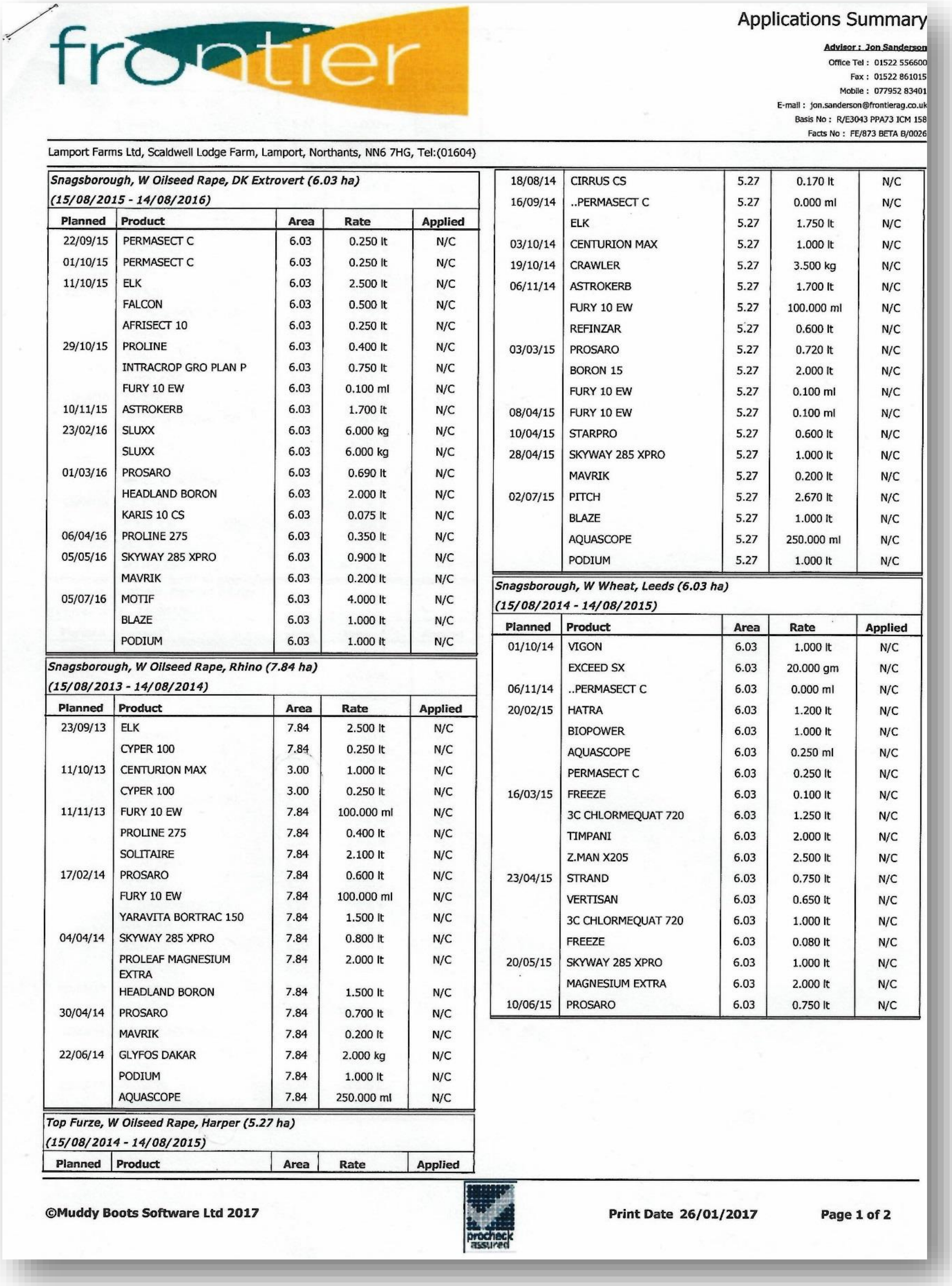
| **Väderstad wheel** | *Left part* | *Right part* |
|---|---|---|
| Horizontal draught (kN) | 0.05 | 0.05 |
| Vertical force (kN) | 0.69 | 0.75 |

Table 2. Claydon: Mean values for bulk density, penetration resistance and force requirements for both left and right parts of the bin before and after the runs

| **Claydon whole unit** | *Left part* | | *Right part* | |
|---|---|---|---|---|
| | Before run | After run | Before run | After run |
| Bulk density (Mg m$^{-3}$) | 1.47 c | 1.54 b | 1.61a | 1.66 a |
| Penetration (MPa) (0-50mm) | 1.13 ab | 1.15 a | 1.23 a | 1.20 a |
| Penetration (MPa) (150-200 mm) | 1.46 c | 1.71 b | 2.10 a | 1.95 a |
| Horizontal draught (kN) | 0.74 | | 1.50 | |
| Vertical force (kN) | 0.19 | | 0.59 | |

| **Claydon seeder** | *Left part* | *Right part* |
|---|---|---|
| Horizontal draught (kN) | 0.05 | 0.04 |
| Vertical force (kN) | -0.01 | -0.02 |

# Appendix C: Chemicals application for both fields during 2014-2016 (after Frontier Agriculture Ltd.)



frontier

Applications Summary

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***Snagsborough, W Oilseed Rape, DK Extrovert (6.03 ha)***
***(15/08/2015 - 14/08/2016)***

| Planned | Product | Area | Rate | Applied |
|---|---|---|---|---|
| 22/09/15 | PERMASECT C | 6.03 | 0.250 lt | N/C |
| 01/10/15 | PERMASECT C | 6.03 | 0.250 lt | N/C |
| 11/10/15 | ELK | 6.03 | 2.500 lt | N/C |
|  | FALCON | 6.03 | 0.500 lt | N/C |
|  | AFRISECT 10 | 6.03 | 0.250 lt | N/C |
| 29/10/15 | PROLINE | 6.03 | 0.400 lt | N/C |
|  | INTRACROP GRO PLAN P | 6.03 | 0.750 lt | N/C |
|  | FURY 10 EW | 6.03 | 0.100 ml | N/C |
| 10/11/15 | ASTROKERB | 6.03 | 1.700 lt | N/C |
| 23/02/16 | SLUXX | 6.03 | 6.000 kg | N/C |
|  | SLUXX | 6.03 | 6.000 kg | N/C |
| 01/03/16 | PROSARO | 6.03 | 0.690 lt | N/C |
|  | HEADLAND BORON | 6.03 | 2.000 lt | N/C |
|  | KARIS 10 CS | 6.03 | 0.075 lt | N/C |
| 06/04/16 | PROLINE 275 | 6.03 | 0.350 lt | N/C |
| 05/05/16 | SKYWAY 285 XPRO | 6.03 | 0.900 lt | N/C |
|  | MAVRIK | 6.03 | 0.200 lt | N/C |
| 05/07/16 | MOTIF | 6.03 | 4.000 lt | N/C |
|  | BLAZE | 6.03 | 1.000 lt | N/C |
|  | PODIUM | 6.03 | 1.000 lt | N/C |

***Snagsborough, W Oilseed Rape, Rhino (7.84 ha)***
***(15/08/2013 - 14/08/2014)***

| Planned | Product | Area | Rate | Applied |
|---|---|---|---|---|
| 23/09/13 | ELK | 7.84 | 2.500 lt | N/C |
|  | CYPER 100 | 7.84 | 0.250 lt | N/C |
| 11/10/13 | CENTURION MAX | 3.00 | 1.000 lt | N/C |
|  | CYPER 100 | 3.00 | 0.250 lt | N/C |
| 11/11/13 | FURY 10 EW | 7.84 | 100.000 ml | N/C |
|  | PROLINE 275 | 7.84 | 0.400 lt | N/C |
|  | SOLITAIRE | 7.84 | 2.100 lt | N/C |
| 17/02/14 | PROSARO | 7.84 | 0.600 lt | N/C |
|  | FURY 10 EW | 7.84 | 100.000 ml | N/C |
|  | YARAVITA BORTRAC 150 | 7.84 | 1.500 lt | N/C |
| 04/04/14 | SKYWAY 285 XPRO | 7.84 | 0.800 lt | N/C |
|  | PROLEAF MAGNESIUM EXTRA | 7.84 | 2.000 lt | N/C |
|  | HEADLAND BORON | 7.84 | 1.500 lt | N/C |
| 30/04/14 | PROSARO | 7.84 | 0.700 lt | N/C |
|  | MAVRIK | 7.84 | 0.200 lt | N/C |
| 22/06/14 | GLYFOS DAKAR | 7.84 | 2.000 kg | N/C |
|  | PODIUM | 7.84 | 1.000 lt | N/C |
|  | AQUASCOPE | 7.84 | 250.000 ml | N/C |

***Top Furze, W Oilseed Rape, Harper (5.27 ha)***
***(15/08/2014 - 14/08/2015)***

| Planned | Product | Area | Rate | Applied |
|---|---|---|---|---|
| 18/08/14 | CIRRUS CS | 5.27 | 0.170 lt | N/C |
| 16/09/14 | ..PERMASECT C | 5.27 | 0.000 ml | N/C |
|  | ELK | 5.27 | 1.750 lt | N/C |
| 03/10/14 | CENTURION MAX | 5.27 | 1.000 lt | N/C |
| 19/10/14 | CRAWLER | 5.27 | 3.500 kg | N/C |
| 06/11/14 | ASTROKERB | 5.27 | 1.700 lt | N/C |
|  | FURY 10 EW | 5.27 | 100.000 ml | N/C |
|  | REFINZAR | 5.27 | 0.600 lt | N/C |
| 03/03/15 | PROSARO | 5.27 | 0.720 lt | N/C |
|  | BORON 15 | 5.27 | 2.000 lt | N/C |
|  | FURY 10 EW | 5.27 | 0.100 ml | N/C |
| 08/04/15 | FURY 10 EW | 5.27 | 0.100 ml | N/C |
| 10/04/15 | STARPRO | 5.27 | 0.600 lt | N/C |
| 28/04/15 | SKYWAY 285 XPRO | 5.27 | 1.000 lt | N/C |
|  | MAVRIK | 5.27 | 0.200 lt | N/C |
| 02/07/15 | PITCH | 5.27 | 2.670 lt | N/C |
|  | BLAZE | 5.27 | 1.000 lt | N/C |
|  | AQUASCOPE | 5.27 | 250.000 ml | N/C |
|  | PODIUM | 5.27 | 1.000 lt | N/C |

***Snagsborough, W Wheat, Leeds (6.03 ha)***
***(15/08/2014 - 14/08/2015)***

| Planned | Product | Area | Rate | Applied |
|---|---|---|---|---|
| 01/10/14 | VIGON | 6.03 | 1.000 lt | N/C |
|  | EXCEED SX | 6.03 | 20.000 gm | N/C |
| 06/11/14 | ..PERMASECT C | 6.03 | 0.000 ml | N/C |
| 20/02/15 | HATRA | 6.03 | 1.200 lt | N/C |
|  | BIOPOWER | 6.03 | 1.000 lt | N/C |
|  | AQUASCOPE | 6.03 | 0.250 ml | N/C |
|  | PERMASECT C | 6.03 | 0.250 lt | N/C |
| 16/03/15 | FREEZE | 6.03 | 0.100 lt | N/C |
|  | 3C CHLORMEQUAT 720 | 6.03 | 1.250 lt | N/C |
|  | TIMPANI | 6.03 | 2.000 lt | N/C |
|  | Z.MAN X205 | 6.03 | 2.500 lt | N/C |
| 23/04/15 | STRAND | 6.03 | 0.750 lt | N/C |
|  | VERTISAN | 6.03 | 0.650 lt | N/C |
|  | 3C CHLORMEQUAT 720 | 6.03 | 1.000 lt | N/C |
|  | FREEZE | 6.03 | 0.080 lt | N/C |
| 20/05/15 | SKYWAY 285 XPRO | 6.03 | 1.000 lt | N/C |
|  | MAGNESIUM EXTRA | 6.03 | 2.000 lt | N/C |
| 10/06/15 | PROSARO | 6.03 | 0.750 lt | N/C |

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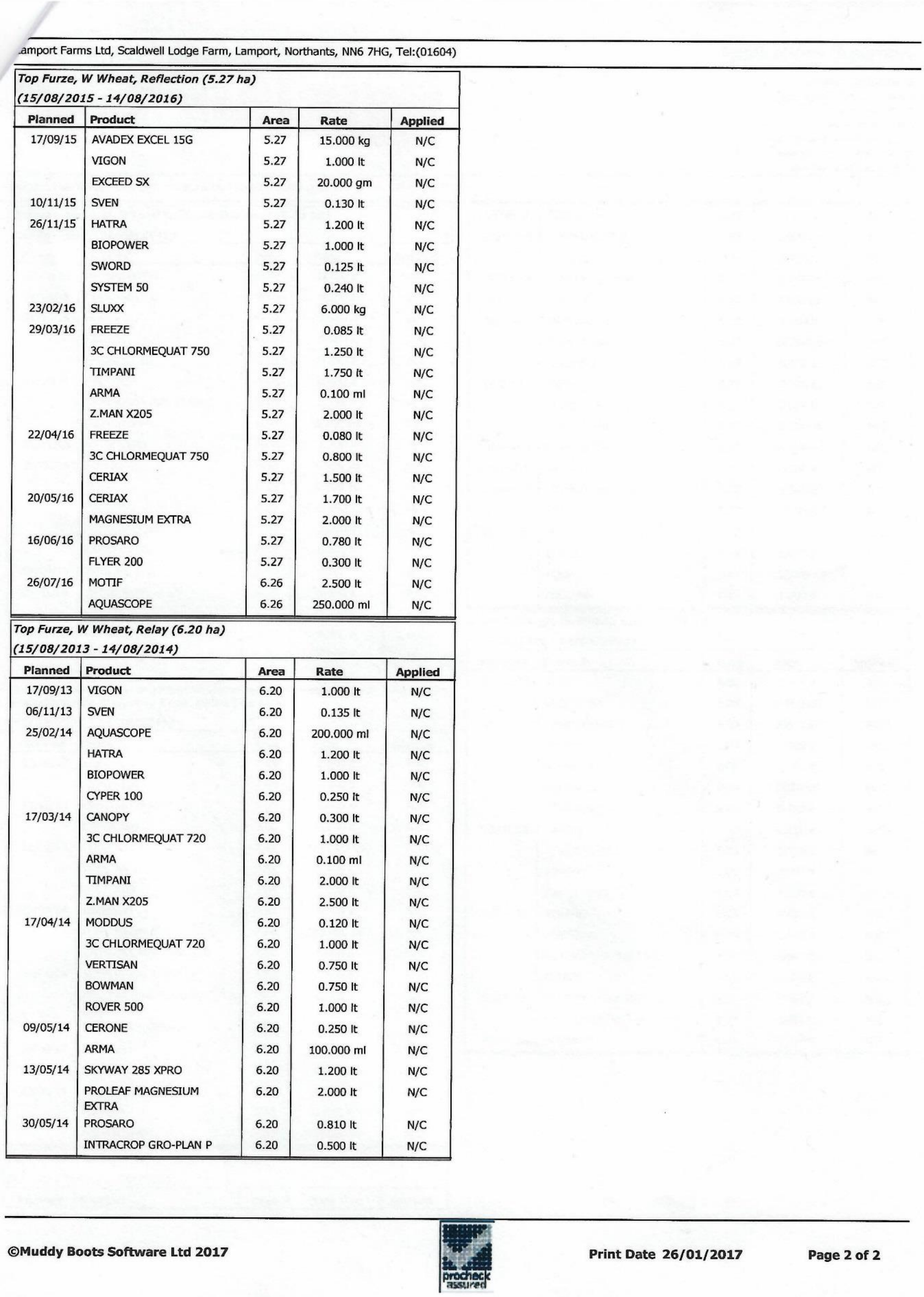

amport Farms Ltd, Scaldwell Lodge Farm, Lamport, Northants, NN6 7HG, Tel:(01604)

***Top Furze, W Wheat, Reflection (5.27 ha)***
***(15/08/2015 - 14/08/2016)***

| Planned | Product | Area | Rate | Applied |
|---|---|---|---|---|
| 17/09/15 | AVADEX EXCEL 15G | 5.27 | 15.000 kg | N/C |
| | VIGON | 5.27 | 1.000 lt | N/C |
| | EXCEED SX | 5.27 | 20.000 gm | N/C |
| 10/11/15 | SVEN | 5.27 | 0.130 lt | N/C |
| 26/11/15 | HATRA | 5.27 | 1.200 lt | N/C |
| | BIOPOWER | 5.27 | 1.000 lt | N/C |
| | SWORD | 5.27 | 0.125 lt | N/C |
| | SYSTEM 50 | 5.27 | 0.240 lt | N/C |
| 23/02/16 | SLUXX | 5.27 | 6.000 kg | N/C |
| 29/03/16 | FREEZE | 5.27 | 0.085 lt | N/C |
| | 3C CHLORMEQUAT 750 | 5.27 | 1.250 lt | N/C |
| | TIMPANI | 5.27 | 1.750 lt | N/C |
| | ARMA | 5.27 | 0.100 ml | N/C |
| | Z.MAN X205 | 5.27 | 2.000 lt | N/C |
| 22/04/16 | FREEZE | 5.27 | 0.080 lt | N/C |
| | 3C CHLORMEQUAT 750 | 5.27 | 0.800 lt | N/C |
| | CERIAX | 5.27 | 1.500 lt | N/C |
| 20/05/16 | CERIAX | 5.27 | 1.700 lt | N/C |
| | MAGNESIUM EXTRA | 5.27 | 2.000 lt | N/C |
| 16/06/16 | PROSARO | 5.27 | 0.780 lt | N/C |
| | FLYER 200 | 5.27 | 0.300 lt | N/C |
| 26/07/16 | MOTIF | 6.26 | 2.500 lt | N/C |
| | AQUASCOPE | 6.26 | 250.000 ml | N/C |

***Top Furze, W Wheat, Relay (6.20 ha)***
***(15/08/2013 - 14/08/2014)***

| Planned | Product | Area | Rate | Applied |
|---|---|---|---|---|
| 17/09/13 | VIGON | 6.20 | 1.000 lt | N/C |
| 06/11/13 | SVEN | 6.20 | 0.135 lt | N/C |
| 25/02/14 | AQUASCOPE | 6.20 | 200.000 ml | N/C |
| | HATRA | 6.20 | 1.200 lt | N/C |
| | BIOPOWER | 6.20 | 1.000 lt | N/C |
| | CYPER 100 | 6.20 | 0.250 lt | N/C |
| 17/03/14 | CANOPY | 6.20 | 0.300 lt | N/C |
| | 3C CHLORMEQUAT 720 | 6.20 | 1.000 lt | N/C |
| | ARMA | 6.20 | 0.100 ml | N/C |
| | TIMPANI | 6.20 | 2.000 lt | N/C |
| | Z.MAN X205 | 6.20 | 2.500 lt | N/C |
| 17/04/14 | MODDUS | 6.20 | 0.120 lt | N/C |
| | 3C CHLORMEQUAT 720 | 6.20 | 1.000 lt | N/C |
| | VERTISAN | 6.20 | 0.750 lt | N/C |
| | BOWMAN | 6.20 | 0.750 lt | N/C |
| | ROVER 500 | 6.20 | 1.000 lt | N/C |
| 09/05/14 | CERONE | 6.20 | 0.250 lt | N/C |
| | ARMA | 6.20 | 100.000 ml | N/C |
| 13/05/14 | SKYWAY 285 XPRO | 6.20 | 1.200 lt | N/C |
| | PROLEAF MAGNESIUM EXTRA | 6.20 | 2.000 lt | N/C |
| 30/05/14 | PROSARO | 6.20 | 0.810 lt | N/C |
| | INTRACROP GRO-PLAN P | 6.20 | 0.500 lt | N/C |

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# Appendix D: Net present value in Top Furze field (clay)

Table 3. Farm system: estimate of the net present value over 10 years in Top Furze (clay)

| Year | Crop | Revenue[a] | Tillage labour and machinery | Gross margin | Undiscounted net margin | Discounted net margin |
|---|---|---|---|---|---|---|
| | | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) |
| 1 | Wheat | 1256 | 31.2 | 758 | 639 | 639 |
| 2 | Oilseed | 1296 | 19.0 | 857 | 750 | 721 |
| 3 | Wheat | 1101 | 31.2 | 603 | 484 | 447 |
| 4 | Oilseed | 1296 | 19.0 | 857 | 750 | 667 |
| 5 | Wheat | 1256 | 31.2 | 758 | 639 | 546 |
| 6 | Oilseed | 1296 | 19.0 | 857 | 750 | 617 |
| 7 | Wheat | 1101 | 31.2 | 603 | 639 | 382 |
| 8 | Oilseed | 1296 | 19.0 | 857 | 750 | 570 |
| 9 | Wheat | 1256 | 31.2 | 758 | 484 | 467 |
| 10 | Oilseed | 1296 | 19.0 | 857 | 750 | 527 |
| Total | | 12456 | 251.0 | 7771 | 6635 | 5590 |
| Average | | 1245 | 25.1 | 777 | 664 | 559 |

[a]: the wheat yield alternates for the two values measured; the oilseed rape revenue is fixed.

Table 4. Claydon: estimated net present value over 10 years in Top Furze (clay)

| Year | Crop | Revenue | Tillage labour and machinery | Gross margin | Undiscounted net margin | Discounted net margin |
|---|---|---|---|---|---|---|
| | | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) |
| 1 | Wheat | 1322 | 11.2 | 824 | 725 | 725 |
| 2 | Oilseed | 1225 | 11.2 | 786 | 687 | 660 |
| 3 | Wheat | 1045 | 11.2 | 547 | 448 | 414 |
| 4 | Oilseed | 1225 | 11.2 | 786 | 687 | 610 |
| 5 | Wheat | 1322 | 11.2 | 824 | 725 | 619 |
| 6 | Oilseed | 1225 | 11.2 | 786 | 687 | 564 |
| 7 | Wheat | 1322 | 11.2 | 824 | 725 | 573 |
| 8 | Oilseed | 1225 | 11.2 | 786 | 687 | 522 |
| 9 | Wheat | 1045 | 11.2 | 547 | 448 | 327 |
| 10 | Oilseed | 1225 | 11.2 | 786 | 687 | 482 |
| Total | | 12181 | 112.0 | 7496 | 6506 | 5496 |
| Average | | 1218 | 11.2 | 750 | 651 | 550 |

Table 5. Sumo DTS: estimated net present value over 10 years in Top Furze (clay)

| Year | Crop | Revenue | Tillage labour and machinery | Gross margin | Undiscounted net margin | Discounted net margin |
|---|---|---|---|---|---|---|
| | | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) |
| 1 | Wheat | 1321 | 21.4 | 824 | 713 | 713 |
| 2 | Oilseed | 1234 | 21.4 | 786 | 685 | 659 |
| 3 | Wheat | 1056 | 21.4 | 547 | 448 | 414 |
| 4 | Oilseed | 1234 | 21.4 | 786 | 685 | 609 |
| 5 | Wheat | 1321 | 21.4 | 824 | 713 | 610 |
| 6 | Oilseed | 1234 | 21.4 | 786 | 685 | 563 |
| 7 | Wheat | 1321 | 21.4 | 824 | 713 | 564 |
| 8 | Oilseed | 1234 | 21.4 | 786 | 685 | 520 |
| 9 | Wheat | 1056 | 21.4 | 547 | 448 | 327 |
| 10 | Oilseed | 1234 | 21.4 | 786 | 685 | 481 |
| Total | | 12245 | 214.0 | 7560 | 6460 | 5460 |
| Average | | 1224 | 21.4 | 756 | 646 | 546 |

Table 6. Mzuri: estimated net present value over 10 years in Top Furze (clay)

| Year | Crop | Revenue | Tillage labour and machinery | Gross margin | Undiscounted net margin | Discounted net margin |
|---|---|---|---|---|---|---|
| | | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) | (£ ha$^{-1}$) |
| 1 | Wheat | 1366 | 18.5 | 868 | 762 | 762 |
| 2 | Oilseed | 1408 | 18.5 | 969 | 862 | 829 |
| 3 | Wheat | 1141 | 18.5 | 643 | 536 | 496 |
| 4 | Oilseed | 1408 | 18.5 | 969 | 862 | 766 |
| 5 | Wheat | 1366 | 18.5 | 868 | 762 | 651 |
| 6 | Oilseed | 1408 | 18.5 | 969 | 862 | 708 |
| 7 | Wheat | 1366 | 18.5 | 868 | 762 | 602 |
| 8 | Oilseed | 1408 | 18.5 | 969 | 862 | 655 |
| 9 | Wheat | 1141 | 18.5 | 643 | 536 | 392 |
| 10 | Oilseed | 1407 | 18.5 | 969 | 862 | 605 |
| Total | | 13419 | 185.0 | 8735 | 7668 | 6466 |
| Average | | 1342 | 18.5 | 874 | 767 | 647 |

Table 7. Väderstad system: estimated net present value over 10 years in Top Furze (clay)

| Year | Crop | Revenue | Tillage labour and machinery | Gross margin | Undiscounted net margin | Discounted net margin |
|---|---|---|---|---|---|---|
| | | (£ $ha^{-1}$) | (£ $ha^{-1}$) | (£ $ha^{-1}$) | (£ $ha^{-1}$) | (£ $ha^{-1}$) |
| 1 | Wheat | 1365 | 15.6 | 868 | 764 | 764 |
| 2 | Oilseed | 1359 | 15.6 | 920 | 817 | 785 |
| 3 | Wheat | 1111 | 15.6 | 613 | 509 | 471 |
| 4 | Oilseed | 1359 | 15.6 | 920 | 817 | 726 |
| 5 | Wheat | 1365 | 15.6 | 868 | 764 | 653 |
| 6 | Oilseed | 1359 | 15.6 | 920 | 817 | 671 |
| 7 | Wheat | 1111 | 15.6 | 613 | 509 | 402 |
| 8 | Oilseed | 1359 | 15.6 | 920 | 817 | 620 |
| 9 | Wheat | 1365 | 15.6 | 867 | 764 | 558 |
| 10 | Oilseed | 1359 | 15.6 | 920 | 817 | 573 |
| Total | | 13112 | 156.0 | 8429 | 7395 | 6223 |
| Average | | 1311 | 15.6 | 843 | 739 | 622 |