The effect of cover crops on soil structure and the subsequent yield of sugar beet

By:

Jake Peter Richards

(BSc Agricultural and Crop Science)

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

Abstract

Pressure is mounting on policy makers and farmers to improve the sustainability of UK Agriculture. One area of improvement surrounds possible changes within crop rotations to improve soil health in tandem with increasing crop yield.

The success of a cash crop, is widely determined by the structure of its growing media. In field crops this is considered as the structure of the soil which is responsible for allowing water and nutrient uptake as well as, particularly for root crops, providing a profile for unimpeded root growth.

The effects of cover crops on the soil physical properties and the subsequent crop growth are considered in this thesis. By conducting glasshouse experiments using different cover crop species and soil volumes, the relationship between cover crop root growth, soil moisture and soil aggregation has been tested. This informed the development of a number of field experiments that have investigated the relationship between cover crops, soil structure and subsequent crop growth with typical UK climatic and soil conditions. It was hypothesised that cover crops improve the soil structure, prior to a cash crop, resulting in higher crop yield.

Our findings have established that cover crops do influence the soil structure, demonstrated by aggregation in controlled environment experiments and soil porosity as seen in the field. However, this was greatly influenced by factors including soil texture, soil volume, cover crop growth and weather conditions. We fund that the growth of cover crops was most beneficial on soils with a low clay content where sugar beet yield was 10% greater following a cover crop than following stubble. This was as a result of lower water stress in response to greater soil porosity.

Results showed that soil with a high clay content is susceptible to changes in soil aggregation. There is a link between soil conductivity and plant growth showing it is a useful proxy for water uptake. There is also a positive effect of cover crops on earthworm population. We found that overall cover crop root growth was directly related to above ground biomass and there was no benefit to combining cover crop species in favour of single species cover crop.

It is concluded that the effect of cover crops, is likely to be positive but their efficacy on soil structure and the subsequent crop growth is highly determined by environmental factors.

Statement of Authorship

The work in this thesis was carried out with the supervision and consultation of my supervisors Prof. Debbie Sparkes, Prof. Sacha Mooney and Dr Mark Stevens.

Practical set up and harvest of the experiments was carried out with the assistance of members of the Sparkes Research Group. Additional practical help was gratefully received from the University and BBRO Trials teams who helped immensely with the harvest of samples.

Where X-ray Computed Tomography was used, the expertise of Dr Brian Atkinson and Dr Craig Sturrock was helpful to set up the scanners and processing the data.

Throughout the thesis the statistics and development of the results sections were written by me with the supervision of Prof. Debbie Sparkes. For Soil conductivity the data presented incorporates figures created by Guillaume Blanchy and Prof. Andrew Binley from Lancaster University.

Table of Contents

Acknowledgements

I would like to take this opportunity to have the time to thank a number of individuals who I have become indebted to during the course of my PhD.

Firstly I must highlight the role played by my Academic supervisors Professor Debbie Sparkes and Professor Sacha Mooney who's expertise have been invaluable in shaping the project and who have been a source of support, inspiration and advice throughout the last four years. It is accurate to say that I have learnt an awful lot about science, and myself from these two people.

I must also thank Dr Mark Stevens (British Beet Research Organisation) and Colin MacEwan (Formerly of BBRO) both for their support in helping me to understand the needs of the sugar beet growers and in their seeing the value of funding PhD students in Applied Crop Research.

For their help in allowing me to use novel and innovative techniques I must thank Dr Brian Atkinson and Dr Craig Sturrock of the Hounsfield X-Ray CT Facility. Similarly Guillaume Blanchy and Professor Andrew Binley from Lancaster University have been a joy to work with and I have no doubt that our work has been a sterling example of scientific collaboration.

Like so many others who have passed through the doors to Sutton Bonington Campus I must thank the expert trials team of John Alcock, Matt Tovey and Will Spracklen for their help with field experiments and the jovial conversations in-between. Similarly the BBRO trials team led by Daniel Godsmark have also been instrumental in the success of the field experiments. I thank James Beamish, Poul Hoveson and Peter & Mark Richards for allowing me to use their fields over the last four years. I must also thank the Sparkes group and UoN Beet Team which has consisted of: Dr Jenny Bussell, Dr Agata Kaczmarek, Dr Tamara Fitters, Dr Kamal Alskaf, Dr Alistair Wright, Georgina Barratt, Annabelle Hunt and Lucy Tillier for their role in being a sounding board for ideas, a source of great entertainment and a reminder of why we do what we do. I am very humbled to say they are my friends. I need to particularly thank Alistair for preventing me from being homeless in the middle of my studies and Georgina who has very patiently put up with me in the final months of writing and finding a job.

It would be sacrilege if I weren't to thank my family or their patience and support both during my PhD and getting me here (And for keeping the question "When are you getting a real job?" to a minimum). So Mum, Dad, Libby and Connie – I thank you.

Finally, to the person who I am indebted to and inspired by the most I must thank my better half Alice for always believing in me. I really couldn't have got here without you.

List of Abbreviations

ANOVA	Analysis of Variance
BBRO	British Beet Research Organisation
C:N	Carbon to Nitrogen ratio
cm	Centimetre
CAP	Common Agricultural policy
^{o}C	Degrees Celsius
DEFRA	Department for Environment Food and Rural Affairs
EFA	Environmental Focus Areas
Fig	Figure
g	gram
g cm^{-3}	grams per cubic centimetre
ha	hectare
kg	kilogram
LSD	Least significant differences
mm	millimetre
m^{2}	square metre
N	Nitrogen
%N	percentage N in dry matter
PAR	Photosunthetically active radiation
RLD	Root length density
SMN	Soil mineral Nitrogen
SOC	Soil organic carbon
SOM	Soil organic matter
SED	Standard error of differences
SEM	Standard error of means
t ha^{-1}	tonnes per hectare
UK	United Kingdom
UoN	University of Nottingham

List of Figures

List of tables

Chapter 1: General Introduction

1.1 Rationale

This PhD project set out to understand the effects of autumn sown cover crops on soil structure and subsequent growth and yield of sugar beet. The project was initiated by the University of Nottingham and the British Beet Research Organisation.

In recent years there has been pressure to modify agricultural practices to improve soil and water quality of UK arable farmland. There are approximately 8.5m ha of arable land in the UK (FAO, 2016). In 2014, research published by Edmondson et al. (2014) suggested that garden allotments have better soil conditions than arable soils, which resulted in widespread media coverage of soil degradation in the UK. In response to reports such as this, there has been increased focus on long term land use and management to mitigate the negative impacts of agriculture on soil. It is expected that legislation will follow the same direction in the coming years with a proposal for farming subsidies to be provided on the basis that farmers will ensure that long term improvements to the environment are made, rather than directly supporting food production.

Recent changes to the Common Agricultural Policy (CAP) have included subsidies for environmental focus areas (EFAs) where farmers are given an additional financial incentive of £85 ha^{-1} to provide EFAs on their land. These can include buffer strips between arable land and watercourses, catch crops, cover crops, nitrogen fixing crops, fallow land and hedges. The inclusion of catch and cover crops is not exclusive to EFAs and many farmers employ these techniques without the additional financial subsidy.

The efficacy of autumn sown catch crops, to prevent nutrient leaching, has been demonstrated several times both within and outside the UK (Grindlay, 1995, Cooper et al., 2017, Vos and van der Putten, 2001, Laine et al., 1993). We have aimed to quantify the effects of cover crops on soil physical properties considering a range of environmental factors such as the soil texture and weather conditions in addition to the management practices employed on individual farms in individual seasons.

The window between the harvest of a cereal crop in summer and the establishment of the sugar beet crop in the following spring gives the opportunity for a cover crop to be established. This means that cover crops could be incorporated into a crop rotation without the need for major changes to a farm’s management practices. If it is found that cover crops are able to improve sugar beet growth, through remediation of soil constraints, alongside benefits to nutrient retention and avoidance of soil erosion, there could be immediate incentive to farmers to use them.

The project has used a number of robust sampling methods to assess soil conditions and the subsequent sugar beet growth. It will be difficult to compare directly between systems where experiments have been carried out in different locations due to differing management. However, comparing results from the following experiments conducted in controlled environments, replicated experiments and farmers’ fields will allow conclusions to be drawn.

1.2 Literature review

1.2.1 Introduction to UK sugar beet production

Sugar beet (*Beta vulgaris spp*.) is a high value crop grown for sugar production in temperate regions of the world. In 2014, 9.4 Mt sugar beet were processed in the UK to provide 1.4 Mt sugar which is equal to 60% of UK sugar consumption (FAO, 2014). Globally, sugar beet provides around 12% of global sugar production with 88% being produced from sugar cane (FAO, 2018). In 2017 EU quotas on sugar production were removed resulting in freer market trading on the world trade market. As a result there has been major investments of time and research to ensure UK production is efficient and able to compete with other beet producing countries and sugar cane production.

In the UK, sugar beet production is limited to the east of the country taking in the counties of Essex, Suffolk, Norfolk, Cambridgeshire, Lincolnshire and South Yorkshire - the areas surrounding the four British Sugar processing factories. The crop provides a break crop from typical arable rotations of winter cereals, oilseed rape, potatoes and legumes.

1.2.2 The sugar beet crop

Sugar beet (*Beta vulgaris*) is a naturally biennial species. During the first year of growth the plant produces a large sucrose filled storage root. Over following the winter the plant becomes vernalised (Wood and Scott, 1975, Bernier et al., 1993) before the plant enters reproductive growth the following growing season. As a result, commercially grown sugar beet is sown in spring and harvested from early autumn, avoiding vernalisation and reproductive growth (Jaggard and Werker, 1999). The crop is harvested for the root which is achieved by separating the leaf crown from the root and then is delivered to a processing plant where the root is sliced and has the sucrose removed from the root biomass.

Sugar beet yield is directly related to intercepted photosynthetically active radiation (PAR) (Milford et al., 1980). This is dependent on the size of the crop canopy. The appearance and growth of sugar beet leaves is determined by accumulated thermal time above a base temperature of 1°C (Milford et al., 1985c). In addition leaf expansion is influenced mostly by thermal time accumulated above a base temperature of 3°C (Milford et al., 1985d). In order to absorb the maximum PAR during the growing season, it is a priority to maximise leaf canopy size as early in the growing season as possible (Scott et al., 1973). Canopy expansion in the spring is slow as leaf expansion is dependent on air temperature (Jaggard and Werker, 1999).

As sugar beet can be vernalised at cool temperatures a trade-off exists between lengthening the growing season for canopy growth and PAR interception, and the need to avoid reproductive growth. Varieties that have a higher vernalisation requirement are now common place. Current UK advice is to drill as soon after the 1st March as possible (Jaggard et al., 2009, Gummerson, 1989, Jaggard and Werker, 1999). This allows for the daytime temperature to be more favourable to leaf growth than vernalisation.

Vernalisation of sugar beet is not well defined and varies depending on the genetics of the line. In general however, plants are at risk of vernalisation when the shoot apex is subjected to a period of cool temperatures (Bernier et al., 1993). The vernalisation requirement has been seen to vary depending on genotypic differences but crops are at risk of vernalisation when temperatures remain below 12^{o}C for 40 days (Milford et al., 2010). Partial vernalisation can occur when seeds on a maturing plant experience cool temperatures (Smit, 1983). Despite vernalisation almost guaranteeing flowering of a plant, it is only the process where the plant is prepared for reproductive growth; the stimulus for the plant to flower is more likely to be photoperiod, irradiance and water supply (Bernier et al., 1993). As a result, vernalisation can be reversed if a plant experiences a period of high temperatures (Smit, 1983). This was also seen to be possible when the seed is going through imbibition. Durrant et al. (1993) found that steeping the seeds in water warmer than 20^{o}C and then air drying was suitable time for devernalisation to occur. This has led to significant improvements in seed priming technology and has contributed to earlier drilling.

Reproductive growth is negative for commercial crops for three main reasons. Firstly, when a sugar beet plant enters reproductive growth, more biomass is partitioned to the production of inflorescence at the expense of sucrose accumulation in the root resulting in a lower sugar content of individual plants (Jaggard et al., 1983). Secondly, when a sugar beet plant produces an inflorescence, its tall stem can cause shading of the surrounding crops. It has been estimated that a single plant in reproductive growth every square metre can reduce the yield of the crop by 11% (Jaggard and Werker, 1999). Finally, if a sugar beet is allowed to flower and produce seeds a considerable number of seeds can be returned to the weed seed bank (Longden et al., 2002). Due to the likely vernalisation of these weed seeds, when germination occurs they will enter reproductive growth and become a further problem for shading and subsequent weed seed return.

1.2.2.2 Sugar beet from a grower's perspective

Unlike most arable crops, sugar beet is distributed mostly by proximity to a sugar factory. In the UK there are currently four British Sugar factories based in Newark, Lincolnshire; Wissington, Norfolk; Cantley, Norfolk; Bury St Edmunds, Suffolk (Draycott, 2006). Currently the delivery allowance is paid to growers who deliver sugar beet from less than 50 miles radius from the factories, making it unprofitable for growers further away to grow sugar beet.

Currently 60% of UK sugar is produced in the UK from approximately 100,000 ha mainly in Lincolnshire, Cambridgeshire, Norfolk and Suffolk. Yields vary considerably depending on the soil texture and area of the field but average yields are approximately 80t ha^{-1}. Typical sugar contents of modern varieties are 18% sucrose and increasing every year. In the factory beet is paid for by adjusting all beet deliveries to 16% sucrose content. The current price paid for an adjusted tonne of sugar beet is £19.07 t^{-1} (Nix, 2019). Cereal production will be the mainstay for the crop rotation for these farms but due to the gross margin of sugar beet which is approximately £600 ha^{-1} (Nix, 2019) they are an attractive break crop. In addition, the genetic distance between sugar beet and other typical field crops offers the grower more opportunities for weed control which is a particular problem for UK arable farmers. In addition to this the autumn-winter harvest of the crop means cash flow continues into the winter which offers more financial stability for many farmers who rely on post-harvest income from cereal crops.

Overall, the UK sugar beet industry contributes £…m to the UK economy and is an important part of UK agriculture.

1.2.2.3 Seed technology

Modern sugar beet seed is primed and pelleted. Priming is the act of washing and steeping seeds in water for a period of time to start the imbibition of the seed (Murray et al., 1993). When imbibition has commenced, seeds are dried and pelleted. Pelleting of the seeds involves coating them with clay to provide spherical pellet. As sugar beet seed is naturally star shaped, it is difficult to drill accurately, and the pellet allows better transport of the seed from the drill to the seedbed.

The composition of the pellet also allows delivery of soil moisture to the seedling which can increase the speed of germination and reduce the risk of the seedling drying out (Durrant and Loads, 1986). Pelleted seed can also be coated with crop protection chemicals such as pyrethroid pesticides to control soil borne pests and aphids, reducing the need for foliar applications of pesticides (Asher and Hanson, 2006).

Sugar beet is advised to be drilled to a stand of 100,000 plants ha^{-1} in rows of 45-50cm apart (Jaggard et al., 2011, Jaggard, 1979). In order to reach maximum ground cover plants have to achieve a leaf area index (LAI) of 3 (Jaggard, 1979). A population between 80,000-100,000 plants ha^{-1} has been found to be optimum for the crop. However, Jaggard (1979) also found that if gaps between sugar beet plants exceed 40cm the crop is unable to compensate and maximum canopy cover cannot be achieved. Gaps in the crop are related almost entirely to germination and establishment of the crop.

1.2.2.4 Germination, emergence and establishment

In order to achieve the desired plant population of 100,000 plants ha^{-1} growers normally drill seed at a higher rate of approximately 120,000 seeds ha^{-1} and aim for 90% establishment. In order to achieve good establishment seeds must germinate, emerge and reach full canopy ground cover. Optimal establishment can be achieved when seeds are drilled into seedbeds with moderate soil consolidation that allows good seed-soil contact, promoting imbibition and germination (Blunk et al., 2017).

1.2.2.5 Seed-soil contact

One major factor influencing crop establishment is seed-soil contact. Good seed-soil contact is highly influenced by the seedbed (Blunk et al., 2018, Blunk et al., 2017). In all crops it is necessary to have good contact between the seed and soil. This allows for movement of water from the soil to the seed where it is absorbed leading to imbibition, the first stage of germination (Atkinson et al., 2007). Good seed-soil contact usually requires a uniform, shallow, seedbed with a large proportion of small aggregates (<2 mm diameter). Aggregates with a larger diameter can cause seedlings to experience difficulty emerging from the seedbed (Hakansson et al., 2006). In addition, moderate consolidation of the soil surface immediately after drilling has been shown to allow closer contact between soil aggregates and the pelleted seed (Arvidsson et al., 2012).

1.2.2.6 Limitations to sugar beet emergence

Limitations to sugar beet emergence and establishment have been relatively well explored. As previously discussed, seed-soil contact is required in order for the seed to absorb water. Therefore, soil moisture content is an important factor. Hunter and Erickson (1952) suggested that sugar beet are more sensitive to soil moisture than cereal crops in that they require a relatively higher moisture content for germination. However, Perry (1973) highlighted the fact that sugar beet are also sensitive to seedbeds with excess moisture which can provide inhospitable conditions for sugar beet seedlings. This was attributed to the production of anaerobic conditions which are unfavourable for the sugar beet seedlings. Excess water can also result in the formation of crusts in sandy and silt soils (Wakindiki and Ben-Hur, 2002). This can be unfavourable for sugar beet seedlings to push through if the surface is well dried which can result in seedling death and patchy, sporadic establishment (Lehrsch et al., 2005).

1.2.2.7 Seedbed preparation

In order to create an even seedbed on varying soil textures, different tillage techniques are used. Typical practice on soils with a high clay content is ploughing during the autumn which allows freeze-thaw cycles during the winter to break down plough furrows for the spring (Wang et al., 2012). The high water holding capacity of clay soils means they are at risk of becoming massive and cloddy which, if not remediated, can be a problem for seedbed evenness. To counter this clay soils are often power harrowed immediately prior to drilling to ensure a fine tilth for the seedbed (Larney et al., 1988).

On light textured soil it is possible for minimum tillage to be acceptable without the need for harrowing or power harrowing in spring. The relatively low water holding capacity of sand compared to clay and the low risk of the soil becoming cloddy means producing an even seedbed is relatively simple.

In recent years, with developments in tillage and drilling equipment, there has been some research focussing on using reduced tillage techniques. Reducing the intensity of tillage is an attractive prospect for farmers as conventional ploughing systems tend to be more expensive and time consuming. Findings from the 1970s suggest that reduced, or direct tillage doesn’t lead to yield penalties for winter wheat and spring barley (Ellis et al., 1979). Furthermore, it has been found that using direct drilling methods decreases the risk of soil compaction (Richard et al., 1995). However, field experiments showed that direct drilling of sugar beet did lead to an increase in predator damage of sugar beet seedlings, which resulted in poorer establishment (Richard et al., 1995). Similarly, Koch et al. (2009) and Morris et al. (2007) found that strip tillage led to poor establishment of sugar beet resulting in significant reductions in yield.

1.2.2.8 Drilling date

Sugar beet have a base temperature of $3^{o}C$ for growth and development (Milford et al., 1985b, Milford et al., 1985a). It is therefore a priority for sugar beet to be drilled as early in spring as soil temperatures are above $3^{o}C$. Drilling date of sugar beet has slowly become earlier in the year. During the 1980s recommendations were that sugar beet in the UK should not be drilled until after the 20 March (Durrant and Jaggard, 1988). Breakthroughs in priming in the late 1980s resulted in drilling being viable approximately 10 days earlier (Durrant et al., 1993). Drilling is now typically from the 1 March and continues normally until the end of April (BBRO, 2019). Soils with a high water content will take longer to heat up in the spring. There is a strong correlation between soils with a high clay content and high water holding capacity (Easton and Bock, 2016). Therefore, soils with a high clay content are likely to take longer to reach temperatures above the 3^{o}C threshold for drilling than sandy or silt soils. As a result drilling on clay soils is typically carried out later than sandy soils.

1.2.2.9 The importance of good rooting

In order to achieve a good water supply, a good root system is essential. While overall growth of sugar beet is linked to temperature (Milford et al., 1985b) and intercepted light (Scott and Jaggard, 1978), soil conditions has a large influence on the growth of the root system. In an average growing season, a mature sugar beet rooting system will be developed to a depth of 120 cm (Brown and Biscoe, 1985). However, the majority of rooting will occur in the first 20cm of the soil profile as the root system expands laterally and vertically through the season. Brown and Biscoe (1985) have suggested that 80% of the water used by the crop is sourced from the top 30 cm of the soil profile, highlighting the importance of a good structured top-soil for water uptake.

1.2.2.10 Rooting and water uptake

In the UK, on average 10% of sugar beet yield is not achieved as a result of water stress (Jaggard et al., 1998)(Ober and Rajabi, 2010), a figure that can rise to 25% in drought years. Sandy soils may experience a yield reduction of 5t ha^{-1} if there is a deficit of 200mm water in June (Jaggard et al., 1998). The factors that determine root expansion include nutrient availability, soil water content, soil texture and structure. It is widely regarded that root growth is strongly related to soil water content. As such, where there is higher soil moisture, the root system will expand to exploit the water reserve and make use of it for plant growth. Weaver (1926) compared irrigated and non-irrigated sugar beet to show that the rooting system of sugar beet was considerably larger when irrigated. Given the variability in the soils used for UK sugar beet production, it is highly unlikely on most soils that there would be non-limiting conditions to such a depth and therefore it is possible to assume that water content will play a pivotal role in determining the root proliferation of the crop.

Between June and August, the crop requires 25 mm water per tonne of sucrose accumulated (Jaggard et al., 1998) and as a result requires approximately 350 mm water to produce a yield of 14 t ha^{-1}. Water reserves are typically lower than the demand of the crop for water and therefore sugar beet crops are reliant on rainfall during the growing season. It has been predicted that rainfall events will become more variable and the UK is likely to experience wetter winters and drier summers, putting more pressure on rain fed crop systems (Richter et al., 2006, Okom et al., 2017). As a result, there has been some focus on increasing the ability of the sugar beet crop to make use of soil water reserves. Shaw et al. (2002) suggested that sugar beet is able to respond to drought by producing more roots at depth. Therefore, it has been suggested that deep rooting traits may be useful to exploit to achieve greater water uptake at depth rather than relying on roots in the topsoil to provide for the plant. It is not fully clear why only 20% of the crop's water is obtained from the deeper soil layers however, there have been suggestions that the roots that grow at depth are much thicker and less efficient at transporting water (Brown and Biscoe, 1985). This is likely to be as a result of higher soil bulk densities at depth being less favourable for the growth of fibrous roots that can exploit pockets of water (Clark et al., 2003). However, recent studies have also suggested that even when roots are detected at depth, there will be some delay before they develop the mature xylem structures capable of taking up water (Fitters et al., 2017).

1.2.2.11 Sugar beet nitrogen uptake

In addition to water uptake, the root system has the function of nutrient uptake. The primary role of nitrogen (N) for sugar beet is to produce a large leaf canopy for maximum light interception (Milford et al., 1985b). This is a contrast to most field crops such as wheat and barley which require nitrogen for leaf production but also have a relatively high N requirement for seed production. Leaf area index (LAI) is directly related to nitrogen application (Jaggard and Qi, 2006). Studies have found that, on average, nitrogen uptake of 120 kg ha^{-1} should be sufficient for optimum canopy expansion and achieving a leaf area index of 3.5 (Jaggard et al., 2009, Malnou et al., 2006). As mentioned previously, it is a priority to produce a canopy of 3.5 LAI early in the season to intercept the maximum PAR.

Uptake of N starts from very soon after seedling emergence and continues throughout much of the growing season until August (Durr et al., 2001). However, in order to achieve maximum canopy expansion early in the season, nitrogen fertiliser is applied during the early stages of crop establishment (Malnou et al., 2006, Pocock et al., 1990). Nitrogen is applied at two time points to avoid scorching of the seedlings. N should be applied before the plants reach four true leaves as nitrogen prills can get caught in the shoot apex and remove the meristem, leading to seedling death. Nitrogen from soil and previous crop residues is released throughout the growing season however, this is of limited use to the crop during initial canopy expansion as the requirement is early in the season, and SMN is not sufficient to sustain rapid canopy growth (Cicek et al., 2015). The mineralisation of SMN means that there is also no need for late applications of nitrogen to maintain the canopy in the autumn and winter (Malnou et al., 2008). Nitrogen is also redistributed from senescing leaves to newly emerging leaves and is therefore not lost from the plant during the growing season (Burky and Biscoe, 1983, Scott and Jaggard, 1993a, Malnou et al., 2008).

Above 120 kg N ha^{-1} there is a risk of adverse effects. Excess nitrogen has been shown to increase the production of the impurity amino-nitrogen in the sugar beet (Pocock et al., 1990, Tsialtas and Maslaris, 2005). This makes sucrose more difficult to extract during processing and therefore the extraction process less efficient. Sugar beet that have had excessive nitrogen applied to them have significantly lower shoot to root ratio suggesting that when more N is available for canopy growth, the partitioning of carbohydrate moves away from the root (Brown and Biscoe, 1985, Milford, 1973) as a result excess N availability can lead to large canopies and a reduction in sucrose yield (Jaggard et al., 1999).

1.2.3 Soil physical properties

1.2.3.1 Soil texture

Soil is defined as the matter made of organic and lithic material of the earth (Cousens et al., 1992). Therefore, the soil is thought of as the material made by either sand, silt or clay and the organic material which includes hummus, microorganisms and various soil nutrients. For classification however, soils are thought of as varying contents of sand, silt or clay which can be grouped into many different soil textures (Fig.1.1) (Atterberg, 1905). In the UK, sugar beet production spans a large number of soil textures with characteristics that require specific management.

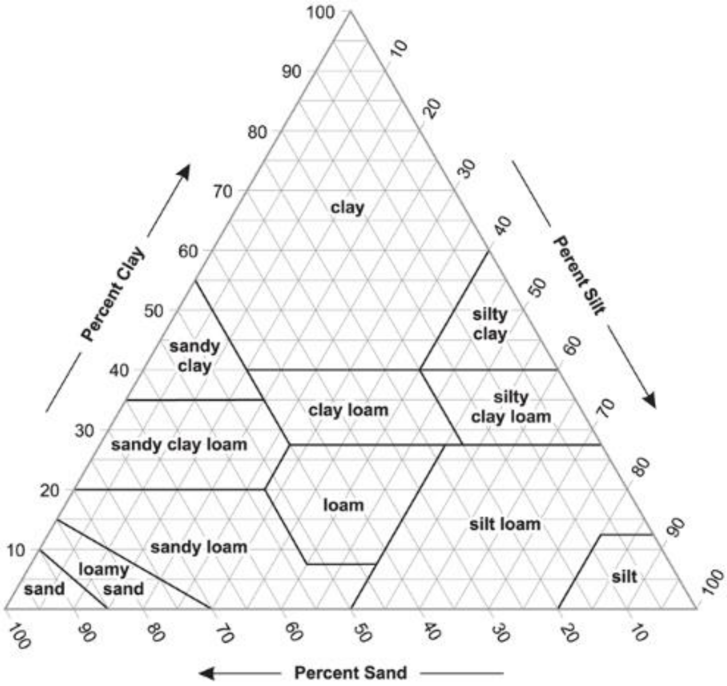


Figure 1.1 Soil type classification dependent on clay, sand and silt content as described by Atterberg, (1905)

1.2.3.2 Soil texture and structure

The structure of soil can be defined as the spatial heterogeneity of the different components or properties of soil (Dexter, 1988). Dexter (1988) explained that the term encompasses the structure at a number of different scales including the arrangement of clods after cultivation as well as the arrangement of clay particles in a floccule. It also encompasses invertebrate life and earthworm channels in the soil profile. Good soil structure can be considered to be stable soil structure.

The structure of soils can normally be described using six different groups (Fig 1.2) (Jahn, 2006). Granular structure soils tend to have a crumbly aggregate distribution and tends to be found in soils that have been cultivated or have seen root activity. Blocky soils occur when soil aggregates increase to sizes greater than 10 mm in diameter which are conditions that are usually remediated by cultivation in agricultural soils. Lower in the soil profile, soils can become prismatic or columnar where large peds form in a vertical axis. Soil that is compacted is likely to show a platy structure where thin layers of soil lay horizontally. In sandy soils, that are not prone to aggregating,

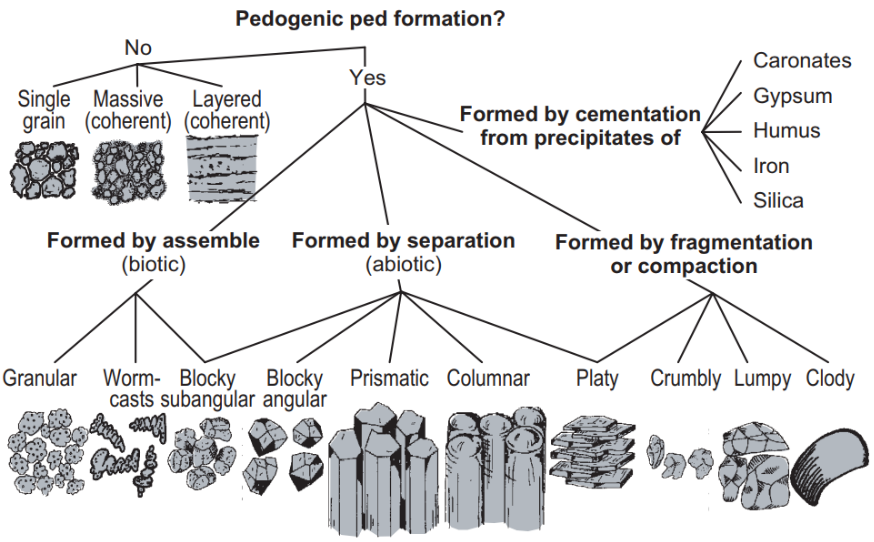


Figure 1.2 Taken from Jahn 2006. Descriptions of structures of soils in terms of aggregation and their formation

structures tend to remain single grains as particles are unable to stick together. Soils can also become massive where all peds and aggregates become consolidated. Massive soils tend to have extremely low porosity and impeded infiltration. A reduction in soil porosity and infiltration are difficult for roots to penetrate and increase the risk of surface run off and soil degradation.

The soil physical properties are important factors in determining the movement of air, water and nutrients through the soil. Maintenance of optimum soil physical properties are required to allow maximum root growth, and crop nutrition. A breakdown in the physical condition of the soil can result in suboptimal performance of crops (Haynes and Naidu, 1998).

Aggregate size distribution is a good measure of the soil physical conditions. Aggregate size has a considerable influence on seed-soil contact and therefore even crop establishment (Blunk et al., 2017, Blunk et al., 2018). In cereal crops, it has been suggested that seedbeds with finer aggregates lead to better establishment of the crop as a result of better seed-soil contact leading to better emergence of the crop (Murungu et al., 2003). Similar findings have been made in sugar beet however, it has been found that consolidation of the top five cm of the seedbed contributes to improving seed-soil contact (Durr and Aubertot, 2000). Moreover, it has been shown that slight compression of the soil has a positive impact on root growth as plants respond positively to the external stimulus (Atkinson et al., 2009, Hakansson et al., 1988)

Logsdon et al. (1987) showed that with increasing soil aggregate size, root diameter of the crop was significantly increased whereas roots were able to move small aggregates and therefore did not experience impedance. It was suggested that this is as a result of increased impedance of the root by the soil which required an increase in pressure exceeded by the root to grow around the aggregates. Logsden et al. (1987) also found that a soil profile with smaller aggregates did not impede growth suggesting that rooting and uptake from the soil profile was more efficient than when roots were impeded.

The impedance of roots can often arise from the formation of compacted layers in the soil profile. Soil compaction can arise from layers in the soil losing porosity and leaving a horizontal layer in the soil with low porosity. Compaction, in the form of plough pans, is likely when arable soils are inverted to the same depth over a number of years, forming a plough pan. Where a plough pan forms, roots and water and air are unable to move through the soil which can result in water logging when rainfall is high and water infiltration is reduced (Lipiec and Hatano, 2003). This can also exacerbate the potential for drought conditions to occur during the growing season if roots are unable to penetrate deep into the soil profile (Kaufmann et al., 2010).

There are contrasting findings on the effect of compaction on sugar beet growth. Generally, it is accepted that sugar beet, winter wheat and barley are less susceptible to compaction than crops such as oats (*Avena sativa*), oilseed rape (*Brassica napus*) and potatoes (*Solarnum tuberosum*) (Arvidsson et al., 2012). Studies normally agree that sugar beet respond positively to a bulk density of 1.1 g m^{-2} compared to 1.0 g m^{-2} which is presumed to be as a result of improved seed-soil contact and movement of moisture to cause imbibition of the seed (Romaneckas et al., 2010). However, it is also accepted that extreme soil compaction, on a field scale, reduces plant population and yield potential (Jaggard, 1977, Hebblethwaite and McGowan, 1980, Arvidsson et al., 2012). Furthermore, impedance of sugar beet roots has been shown to cause fanging of the taproot leading to yield loss through root breakage and financial loss through penalties for soil tare (Koch, 2009, Hoffmann and Schnepel, 2016)

1.2.3.3 Soil water content

Soil moisture content is important for crop growth and has implications for the soil conditions. Soils with high organic matter and high clay content will have the largest water holding capacity (Hudson, 1994, Emerson, 1995). The total amount of water that can be held within the soil before saturation point is known as field capacity. Clay soils are likely to have the largest field capacity. However, this isn't translated directly into available water for the crop as charges on clay particles withhold water from plant roots (Saxton and Rawls, 2006). However, at low water contents, clay prevents water uptake by plants due to relatively higher attraction between water molecules and clay particles compared so sand or silt. Plant available water range peaks in loamy soils and decreases once more with increasing sand content (Fig.1.3). In addition to

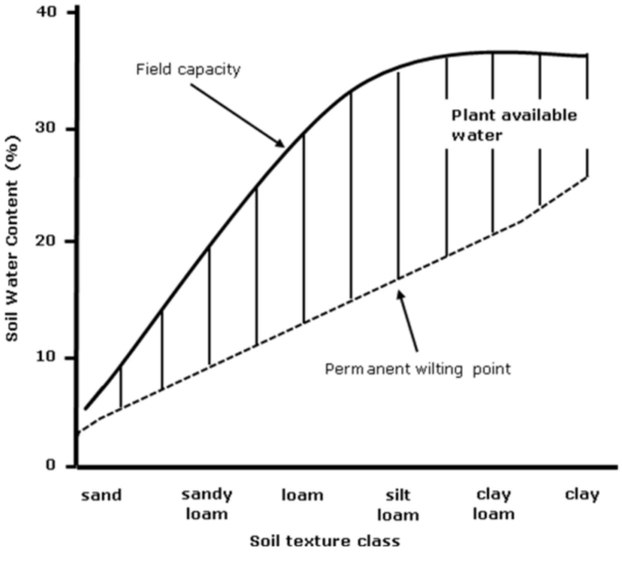


Figure 1.3 Generalised relationship between soil texture and soil water content. (Nature education)

plant available water content, the optimum tillage range is also dependent on clay content.

High water content can be destructive for soils if they are disturbed. Cultivations conducted outside the optimum tillage range can result in loss of aggregation through smearing of soil particles which can result in the production of impermeable layers. Use of heavy machinery at water contents outside the optimum range (Fig.1.4) can result in the compaction of the soil profile making root growth and water movement difficult. Soils that are prone to low soil water content require management in order to prevent excess water loss which may otherwise be used by the crop. This can be a serious consideration to farmers when deciding on crops to grow and whether specific timings of drilling are needed or whether irrigation should be applied.

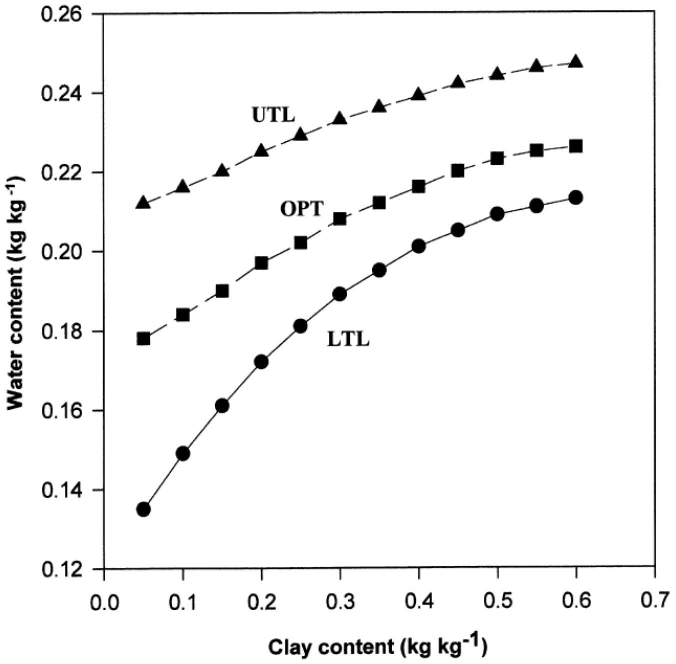


Figure 1.4 Values of upper tillage range (UTL), Optimum tillage limit (OPT) and lower tillage range (LTL) as a function of soil clay content. (Dexter & Bird, 2001).

1.2.3.4 Soil organic matter

As well as soil texture the proportion of soil organic matter (SOM) has a considerable influence on the behaviour of soil. SOM is the portion of the soil created from decaying plant residue, micro-organisms and their secretions. Measurement of SOM is not well defined as organic compounds in the soil will be dependent on respiration of soil microbes. A standard measurement of soil organic matter is loss on ignition where dried soil is burned at 550^{o}C.

Soil organic matter has been linked closely to soil fertility. With increasing SOM soils have been shown to have a higher cation exchange capacity (Johnston, 1986). During the oxidation of SOM nitrogen, potassium and phosphate are released which contributes to the supply of essential nutrients for crop growth. Decaying organic carbon can also stabilise soils with poor structure. Soils with high organic matter have a greater water holding capacity and it has been suggested that this may provide a buffer for crops that experience a short term drought (Johnston et al., 2009). However, the usefulness of this to the crop has been found to be very small (Minasny and McBratney, 2018).

The SOM status of a soil is determined mostly by soil texture and soil use. Undisturbed soils with permanent vegetation such as forests or permanent pasture generally have a higher organic matter than arable soils or short term grass leys. As land use changes, so does the soil organic matter. The SOM status of a soil reaches equilibrium levels that are determined by the use and treatment of the soil. Soils with a higher clay content tend to have higher SOM than sandy or loamy soils under the same conditions as clay is able to stabilise SOM particles in the soil profile. In addition, organic residues can also allow soil particles to aggregate into peds which may improve the soil structure. In arable fields, excess cultivation of soils will result in loss of organic matter whereas growing crops that produce large amounts of fibrous roots will increase organic matter, slightly (Johnston et al., 2009).

Root cropping involves large amounts of soil disturbance which risks decreasing the quantity of organic matter in the soil. Increasing the quantity of SOM present is a slow process. In addition to cropping and cultivation practices, application of imported of organic matter is often carried out. Traditionally this has been achieved by spreading farmyard manure (FYM), slurry or by-products from anaerobic digestion. The contribution of these to SOM is dependent on the carbon to nitrogen (C:N) ratio of the substance. If they have high C:N, nitrogen is likely to be removed from the soil to allow the breakdown of the carbon. This can be avoided with the application of nitrogen fertiliser which increases both crop yield and the return of residues to the soil. However, not all of the applied nitrogen will be used by the crop itself if this is the case. The success of introduced crop residues on the long term SOM status of the soil is limited. Johnston et al. (2009) concluded from a number of long term field experiments that when organic residues are applied with nitrogen fertilisers, an increase of less than 1% was observed after 17 years. It is therefore unlikely that SOM is a useful measure of the impacts of short term cover crops.

1.2.3.5 Soil compaction

Soil compaction can be defined as the rearrangement of soil particles to be closer to one another resulting in an increase in bulk density of the soil. Compaction of the soil can be a naturally occurring phenomenon. However, compaction of agricultural soils is far more prevalent than in uncultivated soils. Modern agricultural practices normally mean that field operations are carried out by heavy machinery. When a piece of machinery is used on an area of soil the risk of compaction is dependent on both the soil conditions and the load that is acting on it. In addition to cultivations outside the optimum tillage range, compaction by agricultural machinery can also occur if cultivations are at the same depth repeatedly, there is a risk of subsoil compaction, whereas reduced cultivation and leaving crop residues has been linked to improved aggregate stability and a reduced susceptibility of soil to compaction (Schjønning and Rasmussen, 1989, Olesen and Munkholm, 2007). Furthermore, after mouldboard ploughing has occurred, soils are highly vulnerable to greater levels of compaction from subsequent passes of tractor tyres than soil that is undisturbed (Arvidsson et al., 2012).

The risk of soil compaction depends on soil organic matter, texture, structure and soil moisture in addition to the pressure put on the soil by the machinery. Similarly soils that have a lower water content will generally be less susceptible to soil compaction (Dexter and Bird, 2001). However, the risk of compaction at high moisture contents is reduced on sandy soils compared to clay soils as soil particles are much larger and tend not to form large aggregates even when compressed. Higher levels of organic matter in a soil provide more resilience to soil compaction by keeping soil particles apart. The impacts of compaction on the soil are many and usually negative. The compression of soil aggregates often leads to a reduction of permeability to water, air and can impede the movement of ions through the soil (Horn et al., 1995). When water is unable to move through the soil to the ground water, surface flow can occur removing sediment from the topsoil. The removal of the topsoil will lead to soil degradation and loss of fertility. As previously mentioned, soil compaction can result in reduced crop growth as root growth is restricted and water and nutrient uptake is inhibited. It has been suggested that a low level of compaction may be beneficial for hydraulic conductivity and root growth however, experiments looking at sugar beet growth under different levels of compaction have shown that soils without compaction generally result in largest crops with highest yields (Arvidsson et al., 2012). Soils that have been heavily compacted require treatment to remove the compacted layers.

1.2.4 Cover crops

1.2.4.1 Introduction to cover crops

In recent years there has been increasing emphasis on ‘soil health’ with policy makers, scientists and farmers globally. In countries such as Brazil, widespread soil erosion that had been linked to over cultivation of soil has resulted in adoption of conservation tillage techniques that aim to reduce soil degradation by preventing soil loss from surface run off during heavy rainfall events and loss of organic matter as a result of oxidation. As a result, zero-tillage systems have been developed and adopted by farmers where crops are established without cultivation of the soil surface. Alongside decisions not to use tillage a greater focus on increasing the quantity of organic matter and incorporating crop residues back into the soil have become more popular. While these techniques don’t completely translate to the agricultural systems in the UK or Europe, modern farming systems and policies are moving in the same direction.

The term ‘cover crop’ is not well defined and can be considered a blanket term for crops with a number of different outputs which are not harvested for a tangible product. Bodner et al. (2010) defined cover crops as plants that are integrated into the rotation between two cash crops.

Some clarity has been provided on the definition of cover crops by the changes to agricultural policy. Since the reform of the Common Agricultural Policy in 2013, farmers have been required to have a proportion of Environmental Focus Areas (EFAs) in order to satisfy ‘greening’ requirements to receive farming subsidies. As a result the terms catch crop and cover crop have been defined legally by the period of time when they are grown (Zinngrebe et al., 2017). EFA catch crops must be established be established by 20 August and must remain in place until 15 October. EFA cover crops must be established before 1 October and must remain in place until 15 February (DEFRA, 2018). In addition to the required growing period of catch and cover crops, EFA cover crops must have at least one cereal species and at least one non-cereal species however, there is no limit to the number of overall species. It is important to note that these rules do not have to be observed if the catch or cover crop is not contributing to EFAs and so it is possible for farmers to use single species cover crops and establish and destroy them outside of the time frames presented above.

Catch crops have the specific aim to reduce nitrate loss from soil during the later summer and early autumn. A number of studies have shown that if good establishment of catch crops is achieved, they are able to absorb nitrate from the soil and prevent run-off and leaching into watercourses (Grindlay, 1995, Cooper et al., 2017).

Where the capture of excess nitrogen is concerned, there is considerable reliable evidence that cover crops can be highly effective at absorbing the nitrogen in the early autumn and preventing leaching that may otherwise have occurred in a bare soil (Cooper et al., 2017, Valkama et al., 2015). Valkama et al. (2015) concluded that, in Nordic countries, species of ryegrass were able to decrease the loss of nitrogen from the soil by 50% whereas legume cover crops were shown to be an ineffective method of reducing nitrate leaching. Cooper et al. (2017) concluded that in the UK oilseed radish (*Raphanus sativus*) cover crops were between 80-90% efficient at reducing the quantity of nitrogen leached compared to bare soil. Cooper et al. (2017) also found that leaching was not able to be controlled by not cultivating the soil alone and that the avoidance of leaching was affected more by crop cover than tillage practice. As a result, from an environmental point of view, using cover crops as a means to avoid excess nitrate loss is highly effective.

1.2.4.2 The role of cover crops in weed suppression

A major challenge for any cropping system is the control of agricultural weeds. Conventional systems are reliant on tillage to mechanically remove weeds and herbicides which offer chemical control of weeds. A recent meta-analysis has suggested that cover crops are effective at suppressing weed growth in the early season but did not allow for sufficient control to avoid yield loss in grain crops (Osipitan et al., 2018). However, it was clear that the suppression of weeds was sufficient for weed control in vegetable and row crops suggesting that they may provide a useful control mechanism for sugar beet. Osipitan et al. (2018) suggested that effective weed control was only achieved as a result of ground cover being able to smother weed seedlings during their early growth. Brust et al. (2014) concluded similar findings but suggested that cover crop species such as mustard and radish may be more effective than phacelia due to their coverage of the soil surface.

In addition to the smothering effect of cover crops, it has been suggested that certain species may suppress weed growth through allelopathy which may also result in negative effects on sugar beet growth (Dhima et al., 2006). Lawley et al. (2012) found that in field conditions, rye did not reduce weed growth through allelopathy but instead out-competed weed species. Furthermore, it appears increasingly likely that in field conditions limitations to sugar beet growth following rye are as a result of denitrification of the seedbed and poorer establishment as a result of excess cover crop residues rather than an allelopathic response (Morris et al., 2009, Wyland et al., 1995)

1.2.4.3 Effect of cover crops on soil physical properties

The effects of cover crops on soil physical properties or soil structure are largely theoretical. The breadth of different soil textures with discreet behaviours under different environmental conditions have proved difficult in comprehensively explaining what effect cover crops have on soil structure. It is widely accepted that soils with a greater proportion of clay will have greater plasticity which suggests that cover crops grown on clay soils may have a greater impact on the aggregation than when cover crops are grown on sandy soils (Keller and Dexter, 2012).

It is generally accepted that plant roots grow through existing channels and exert pressure on the surrounding soil (Goss, 1977). This can lead to changes in the soil porosity with the soil immediately next to roots becoming less porous (Guidi et al., 1985). Soil compression over time is likely to lead to fracturing and production of smaller pores resulting in greater soil porosity (Beven and Germann, 1982). The channels created by roots are important for avoiding soil anaerobic soil conditions and allowing the movement of water through the soil profile (Li and Ghodrati, 1994).

1.2.4.4 Interactions between cover crops and earthworms

Earthworms also contribute to the production of channels through the soil (Jégou et al., 2000). Plant roots and decaying leaf biomass are important food sources for earthworms (Piearce, 1978). As a result, it is difficult to distinguish the differences between root channels created by earthworms and those made by roots as they generally occur in combination. It has been suggested that pores created by roots may have greater structural integrity than earthworm pores due to the lateral pressure exerted by the roots in comparison to ingestion and movement used to create earthworm pores (Blackwell et al., 1990). Nevertheless, the importance of earthworms should not be understated as their activity indicates the recycling and distribution of organic matter through the soil profile and therefore channels made by both should be considered equal in importance.

The abundance of earthworms is heavily dependent on soil texture. Generally, fine textured soils are less suitable to earthworm activity as the coarse crumb structure is thought to be less pleasant for movement and digestion (Edwards and Bohlen, 1996). In addition, soils with heavily clay content, which tend to favour earthworm activity, may be less favourable if the soils are waterlogged (Edwards and Bohlen, 1996).

Tillage, crop rotation and soil disturbance will also affect the earthworm population. In arable fields, where tillage ceases for a period of years, earthworm activity will increase (Wuest, 2001, Ehlers, 1975). At the same time, reduced tillage has been linked to increasing earthworm population as there is reduced damage compared to inversion ploughing (Bertrand et al., 2015).

There have been suggestions that autumn sown cover crops will increase abundance of earthworms during their growth as it provides a food source which would not be available in fallow soil Stroud et al. (2017), Detheridge et al. (2016) however, found that cover crops did not increase the abundance of deep burrowing earthworms, which contribute most to the production of soil channels, due to the long life cycle of the species. This suggests that for increases in deep burrowing earthworms, longer term changes to the disturbance of the soil profile are needed.

Cover crops have been linked to a reduction of soil moisture during their autumn growth (Allison et al., 1998a). Extremes in soil moisture content can affect earthworms in different ways. Generally, low soil moisture content is unfavourable for earthworm movement through the soil as it results in increased soil strength making earthworm activity difficult. Furthermore, high soil moisture content is unfavourable to earthworm growth as it can lead to anaerobic conditions and waterlogging which prevent earthworm activity (Edwards and Bohlen, 1996). Thus, there may be a trade-off between cover crops providing a food source for earthworms and providing optimum conditions for their activity.

1.2.4.5 Effect of cover crops on soil aggregation

The effect of cover crops on soil aggregation is not well understood. Linsler et al. (2016) found that cover crops interacted with freeze-thaw cycles leading to a faster rate of aggregate breakdown in controlled conditions. Field scale experiments have found that changes to aggregate size distribution and stability have been more closely linked to reduced tillage rather than cover cropping itself (Roldan et al., 2003). However, it has been suggested by Gyssels et al. (2005) that plant roots enmesh soil particles which can lead to reduction of macro-aggregate size. Furthermore, it is possible that the drying effect of cover crops in combination with autumn and winter rainfall may also increase the frequency and intensity of wetting and drying cycles which may result in faster break down of large soil aggregates (Utomo and Dexter, 1981)

Aggregation of most soil textures has been shown to be influenced by soil organic carbon (SOC) and clay content (Kay, 1998). SOC has been shown to be an effective substrate for the accumulation of soil particles and micro-organisms which can lead to an increase in soil stability (Angers and Chenu, 1998). However, Angers and Chenu (1998) highlighted that the source of SOC will have great effect on its ability to increase aggregate stability and residues from alfalfa roots are more effective than straw at allowing aggregates to form.

In addition to SOC, aggregate stability has been shown to be increased by root secretions by plants (Morel et al., 1986). It has been suggested that the exudates from plants will increase the stability of the soil leading to better soil structure. However, a number of these theories are based on studies conducted on maize root exudates and therefore can only be used as an indication for the efficacy of different cover crop species on the stability of soil aggregates (Morel, 1991). Further to their effect on soil aggregation, it has been shown that maize root exudates also decrease the penetration resistance of soil and may reduce the negative implications of soil compaction on root growth of subsequent plants (Oleghe et al., 2017).

1.2.4.6 Effect of cover crops on subsequent crop growth

The direct effect of cover crops on cash crop growth has not been well researched. Studies conducted by Richards et al. (1996) and Knott (1996) showed that there was a limited effect of cover crops on the subsequent yield of spring barley and vining peas. Furthermore, while slight differences in growth were measured in some conditions, Allison et al. (1998b) concluded that the financial gains as a result of cover crops did not exceed the financial outlay for their inclusion in the rotation. More recent studies have suggested that cover crop mulches may have increased efficacy when used in combination with reduced or minimum tillage (Glab and Kulig, 2008). However, the lack of consistent findings highlights the need for further experimentation on the effect of cover crops on the yield of sugar beet.

1.3 Research aims

The overall aim of the project was to investigate and quantify the effect of cover crops on the soil physical properties and growth of sugar beet crops.

The fundamental hypothesis is:

"Cover crops improve soil structure resulting in higher sugar beet yield"

To address this, the following sub-hypotheses were used:

1) The impact of cover crops on soil structure is dependent on:
    a. Species rooting characteristics
    b. Air temperature
    c. Species water use
    d. Soil moisture/water availability
    e. Soil texture
    f. Soil volume
2) The growth of cover crops is enhanced by combining different species resulting in an increased impact on soil structure
3) Cover crops improve yield of the subsequent beet crop by improving soil structure which facilitates water and nutrient uptake by the crop

Chapter 2: The effect of tillage radish (*Raphanus sativus*), forage rye (*Secale cereale*) and *Phacelia* on soil physical properties

2.1 Introduction

Anecdotal evidence of the effects of cover crops on soil structure frequently includes suggestions that cover crop roots can alter the soil structure to benefit the following crop. Typically it is the role of tillage to produce a soil profile with an even aggregate distribution and high porosity. These conditions are considered to be conducive to good crop root growth, water and air movement through the soil and overall good crop health (Brown and Biscoe, 1985, Kaufmann et al., 2010, Dexter, 1988).

The hydraulic properties of the soil are strongly influenced by the soil structure. Soil structure, in turn, is heavily influenced by soil texture and aggregation. It is not possible to readily to alter the texture of a particular soil however the aggregation, porosity and organic carbon content of a soil can be manipulated by tillage practice and vegetation (Johnston et al., 2017). In a typical soil structure, soil particles will form aggregates which contain small soil particles. Aggregates vary in size and shape. Aggregate size is dependent on soil texture and management. Aggregates can also be contained within ‘clods’ that are defined as soil that has aggregated to a size of > 25 mm (Dexter, 1988). Soil particles within aggregates will be aligned imperfectly and form intra-aggregate pores which can be air filled or water filled. Inter-aggregate pore space contributes significantly to total soil porosity, however it does not contribute to the macroscale pore connectivity (Dexter, 1988). Therefore, soils with a greater proportion of small aggregates are more likely to have a higher connected pore space than soils with a large proportion of large aggregates.

Inter-aggregate pore space is highly dependent on aggregate size. Pore space between aggregates can be created by plant roots and channels created by soil fauna such as earthworms often termed ‘biopores’. Further changes to porosity can be attributed to tillage. Tillage has the aim of producing a structure with aggregate sizes that allow optimum root growth and pore space that allows movement of air and water through the soil profile (Dexter, 1997). Biopores produced by root channels and earthworm burrows contribute to increasing pore connectivity (Yunusa and Newton, 2003). Whalley et al. (2005) identified that pores created by plant roots are more connected than macropores in bare soil suggesting that they may have a greater effect on hydraulic conductivity and water and air movement through the soil.

Increases in biopores can result in long term increases to soil porosity and hydraulic performance. Changes to soil structure, as a result of cultivation and tillage, are likely to be short term based and may not improve overall water infiltration rates. An interface may be formed between cultivated and uncultivated soil where pore connectivity is low and water is unable to easily pass through soil that has not been cultivated (Williams and Wuest, 2011, Wuest, 2009). Where a soil is massive or has a larger proportion of large aggregates, the macro porosity of the soil is likely to be low. A soil structure with larger aggregates and low porosity is restrictive to fluid movement, water availability and root growth.

In conventional arable systems, damage to the soil structure is often as a result of compaction of the soil. Soil compaction can arise in a number of ways. Surface compaction can occur as a result of compression by machinery or tractor wheels. This level of compaction can readily be removed by cultivation of the top 30 cm of soil if this is the depth of the compaction. A mid-level compaction can occur at the plough level when a pan is created between cultivated and uncultivated soil. At this level, compaction can be alleviated by 'sub-soil cultivation' where machinery can be pulled through the soil just below the layer of compaction causing fissures in the compacted layer. Compaction can also occur below the operational depth of all cultivators. In this case it is often necessary to change cultivation practices entirely and adopt a lower intensity cultivation strategy that allows plant roots and earthworms to remove the layer of compaction over a number of years. Techniques such as minimum or zero tillage that aim to reduce the inversion and disturbance can be employed with the aim of avoiding over-cultivation of the soil.

It is frequently suggested that the easiest method of compaction management is to avoid compaction of the lower layers of the soil profile. However, use of heavy agricultural machinery means it is means the risk of topsoil compaction is high and tillage is the main method used to remediate this. It has been long understood that plant roots influence the aggregation and porosity of the soil (Haynes and Swift, 1990). Using deep rooting crops, prior to a crop for harvest, has been suggested as a method of soil amelioration after soil structural damage and increasing soil salinity in Australian soils (Yunusa and Newton, 2003). Yunusa and Newton (2003) linked the use of thick rooted species being able to grow through layers of compaction to enhanced water use from lower soil layers, where salinity is less limiting. Bodner et al. (2014) made the link between using primer crops to remove salinity in Australian soils and the use of cover crops in temperate regions of the rest of the world. However, the use of cover crops for soil remediation is not a new idea and studies have suggested their use since the 1980s.

The effect of roots on soil structure can occur through a number of mechanisms. Biopores are effective at allowing gas and water exchange through the soil; however, they are ineffective at contributing to water holding capacity. Biopores classed as macropores have been shown to have a greater influence on air permeability and water infiltration than smaller pores (Yunusa and Newton, 2003). It has been suggested that tap rooted species such as lucerne (*Medicago sativa*) and radish (*Raphanus sativa*) may be more effective at creating large macropores through the soil than cereal species that have a lateral, fine root system (Bodner et al., 2014). Furthermore, Whiteley (1989) and Blackwell et al. (1990) suggested that soil around roots is compressed and can therefore produce more stable biopores than pores produced by earthworm movement and those that are produced by tillage.

Roots can also influence the binding of the soil and production of aggregates by root mucilage (Mench et al., 1987, Gregory et al., 2013), and changes to the porosity and aggregation through wetting and drying processes in the soil profile. However, the effectiveness of roots to bind aggregates through secretions of mucilage may be limited and highly dependent on the species, soil moisture content and soil texture (Monroe and Kladivko, 1987, Whiteley, 1989). Cereal species such as rye (*Secale cereale*) and black oat (*Avena strigosa*) have been shown to produce root mucilage that has a binding effect on soil particles and therefore may be more effective at producing stable aggregates in the soil profile. Links have been made between root growth and changes to the macroporosity of soil in controlled conditions (Whalley et al., 2005, Blackwell et al., 1990).

Despite several studies exploring on the effect of roots on the aggregation and porosity of soil, there is a lack of contemporary research on the impact of modern cover crop species on the aggregation of soil. In this experiment, measurements of soil bulk density and total porosity and aggregate size distribution were used to understand the effects of cover crop roots on the soil structure. We aimed to use this initial experiment to test sub-hypotheses: 1a – the effect of cover crop species rooting characteristics on soil structure; and 2 – The growth of cover crops was enhanced when different species were combined resulting in a greater effect on soil structure.

2.2 Materials and methods

2.2.1 Experimental design

A glasshouse experiment was set up at Sutton Bonington Campus, University of Nottingham in April 2016. The glasshouse was temperature controlled to maintain a maximum temperature of 20^{o}C. The cover crop species used were tillage radish (*Raphanus sativus*), forage rye (*Secale cereale*) and *Phacelia.* These cover crops were arranged into 10 separate treatments that contained all combinations of the three species (Table 2.1). Cover crop treatments were grown in 10 litre pots of sandy loam soil for approximately 700^{o}C days. A sandy loam soil was used. The soil was graded to provide a homogenous soil which was poured into pots at a low density before watering to allow soil to settle at a density of 1g.cm^{-3}. Plant pots had a height of 20 cm and a diameter of 20 cm. Degree days were calculated using an assumed base temperature of 0^{o}C. Three plants were grown in each pot and were arranged so all possible combinations of the three treatments were represented including a treatment that was bare, undisturbed soil for the whole experiment (Table 2.1). The experiment was arranged into five blocks which were oriented to account the light and temperature gradient in the glasshouse. Within a block all treatments were randomly arranged meaning that a block can be considered a replicate. Seeds were sown equidistant from each other and the side of the pot. Plants were supplied with drip irrigation to maintain even water supply to all treatments.

Table 2.1. List of cover crop treatments in pot experiment

Treatment	Plants present	Code
1	Tillage radish x 3	TTT
2	Tillage radish x 2, forage rye x 1	TTF
3	Tillage radish x 2, Phacelia x 1	TTP
4	Tillage radish x 1, forage rye x 2	TFF
5	Tillage radish x 1, Phacelia x 2	TPP
6	Tillage radish x 1, forage rye x 2, Phacelia x 1	TFP
7	Forage rye x 3	FFF
8	Phacelia x 3	PPP
9	Forage rye x 2, Phacelia x 1	FFP
10	Forage rye x 1, Phacelia x 2	FPP
11	Bare soil	B

2.2.2 Soil measurements

2.2.2.1 Aggregate size distribution

At the start of the experiment a bulk sample of 500g soil was collected and air dried for three days. At the end of the experiment when final destructive samples were taken, a 500g bulk sample from the centre of each pot was taken at a depth of 10 cm. Samples were sieved for 30 seconds using a stack of sieves with mesh apertures of 10 mm, 6 mm, 5 mm, 4 mm, 3 mm, 2 mm, 1 mm, 500 µm, 50 µm. Samples collected on each sieve after sampling were weighed and used to produce an aggregate size distribution.

Analysis of the aggregate size distribution was carried out in two ways. Mean weight diameter (MWD) was calculated using the formula:

$$\mathbf{MWD} = \sum_{i=1}^{n} \overline{x_i} w_i$$

x_i is the mean diameter of a size range of aggregates separated during the sieving process and w_i is the weight of the aggregates in that size range as a % of the total weight of soil used (Kempner and Rosenau, 1986). This gives a single value for each treatment that can be analysed and compared as an indication of the mean aggregate size. The total distribution can be compared between treatments using the coefficient of uniformity. For this experiment the following equation was used:

$C_u = D90 / D50$

Where D90 is the sieve aperture when 90% of aggregates have cumulatively been caught on a sieve and where D50 is the sieve aperture where 50% of the sample has been collected on a sieve. The C_u therefore provides a single value to account for the MWD.

2.2.2.2 Bulk density and soil water content

At the end of the experiment bulk density samples were taken from three depths: surface, 10 cm and 15 cm. These were taken using a standard sized soil ring of 140 cm^3. Samples were then weighed to two decimal places for fresh weight before being dried at 105°C until a constant weight was achieved. Samples were then removed from the oven and weighed. From the dry weight and volume, soil bulk density was calculated using the following equation.

Soil dry weight (g) / volume (cm^3) = g cm^{-3}

Volumetric water content was also calculated to give an indication of which treatments had the highest water requirements. The water content was calculated here:

$$(Soil\ dry\ weight\ (g))\ \div\ (Soil\ fresh\ weight\ (g))\ \times\ 100$$
$$=\ Volumetric\ water\ content\ (\%)$$

2.2.2.3 Cover crop biomass measurements

At the termination of the experiment, cover crop above ground biomass was collected from each pot. Above ground biomass from each pot was collected as a single sample. Samples were dried at 80°C for a week to achieve a constant dry weight. At this point the samples were weighed to attain cover crop above ground dry biomass.

2.2.2.4 Statistical analysis

Results were analysed using Genstat 19th edition. Analysis of variance, appropriate for a randomised complete block design, was used to explore differences between treatments, and least significant differences (LSDs) calculated automatically by Genstat using the method set out by Fisher (1935). LSD was used as the error bar comparison between treatments showing the smallest difference between treatments that was significant. Linear regression analysis was conducted between above ground biomass, soil water content and aggregate size distribution. The data were tested for normality and homogeneity of variance before analysis.

2.3 Results

2.3.1 Cover crop growth

2.3.1.1 Shoot biomass

Figure 2.1 shows that cover crop treatments produced different amounts of shoot biomass (*P<0.001*). Treatments TTT, TTF, TTP, TFF, TFP, FFF, and TPP produced significantly greater quantities of shoot biomass than PPP, FFP and FPP. There were no differences between TPP and FFP however. With the exception of TPP and FFP, it suggests that treatments containing larger proportions of radish and rye produce more shoot biomass.

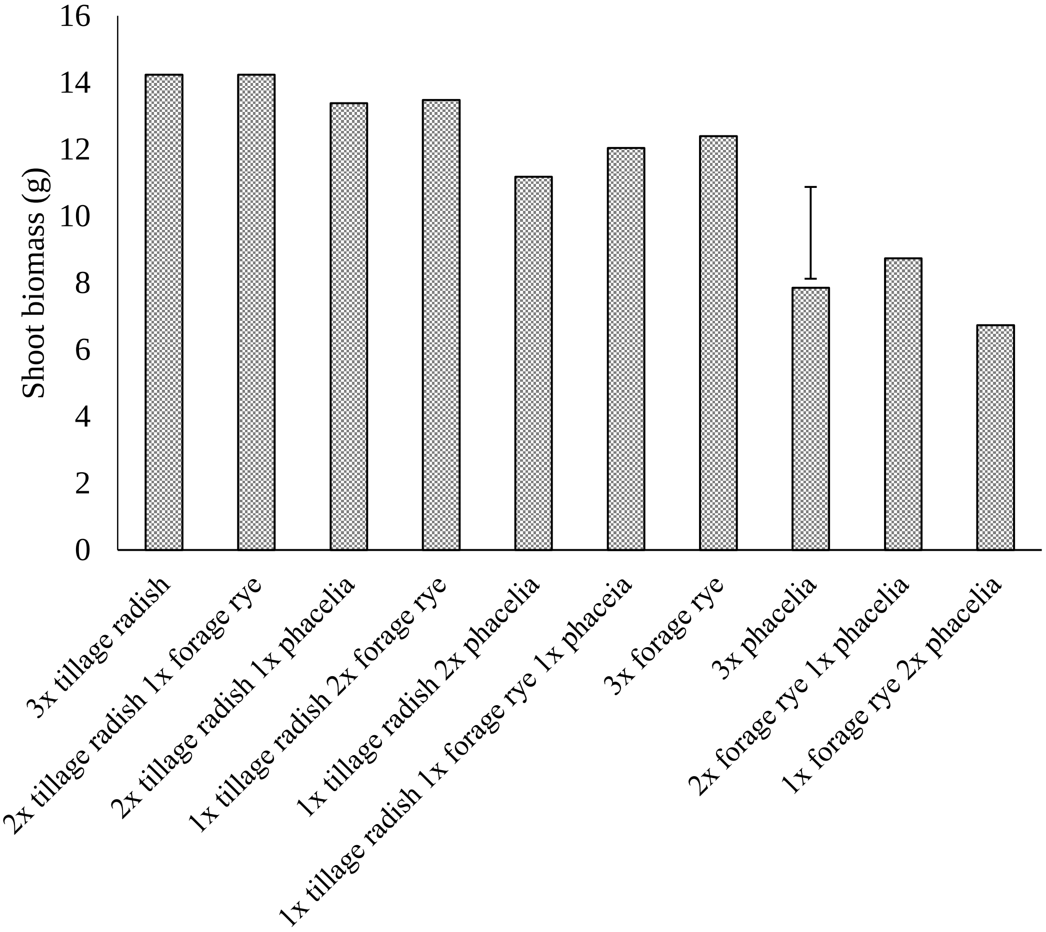


Figure 2.5 Mean above ground biomass (g) of cover crop treatments (Table 2.1) at the end of experiment (*P<0.001*). Error bar represents LSD of 2.744. d.f. 49

2.3.1.2 Biomass and soil moisture

A significant negative relationship was established between increasing shoot biomass and soil moisture (Fig.2.2). This suggests that treatments with a larger quantity of shoot biomass have a higher water requirement and therefore a greater effect on soil moisture.

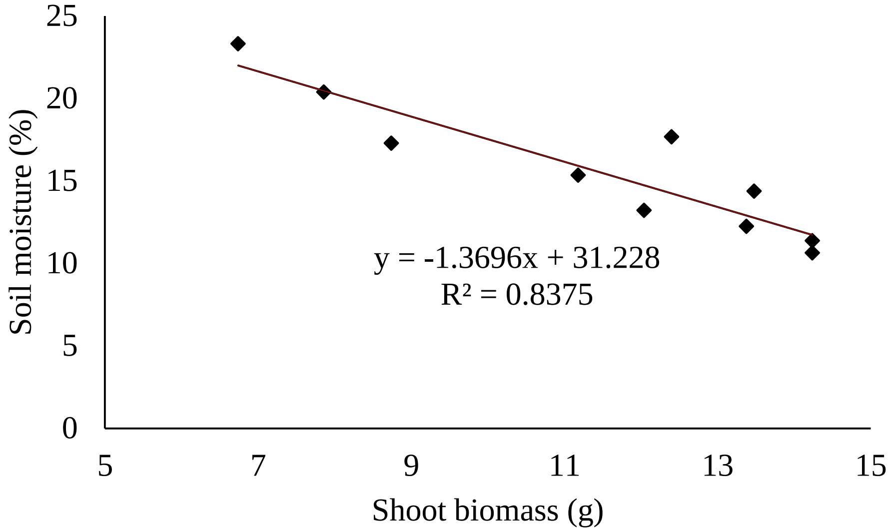


Figure 2.6 Linear regression between above ground and soil moisture (*P=0.004*).

It was also observed that as the proportion of phacelia increased in the treatments there was a negative effect on total shoot biomass (Fig.2.3). This suggests that as the proportion of phacelia increases the soil moisture is likely to be higher. In turn this shows that phacelia compared to tillage radish and rye produces less shoot biomass and will have less of a drying effect on the soil.

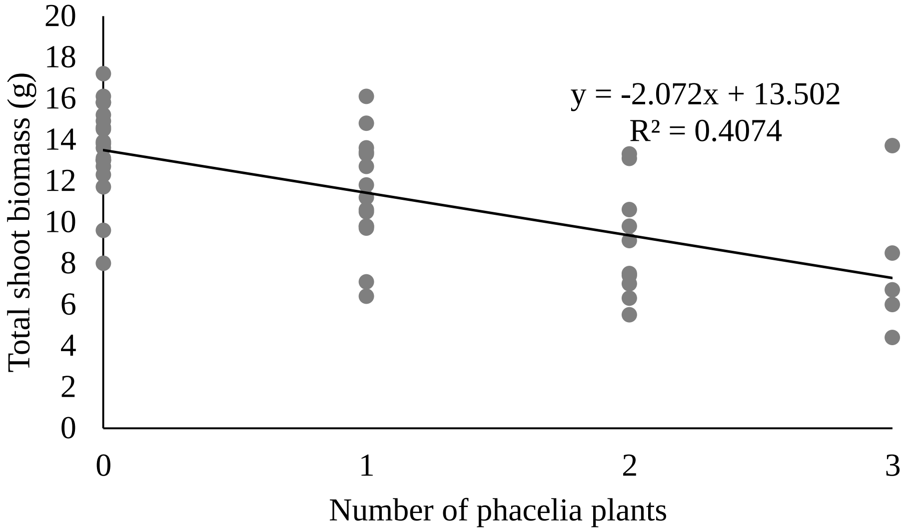
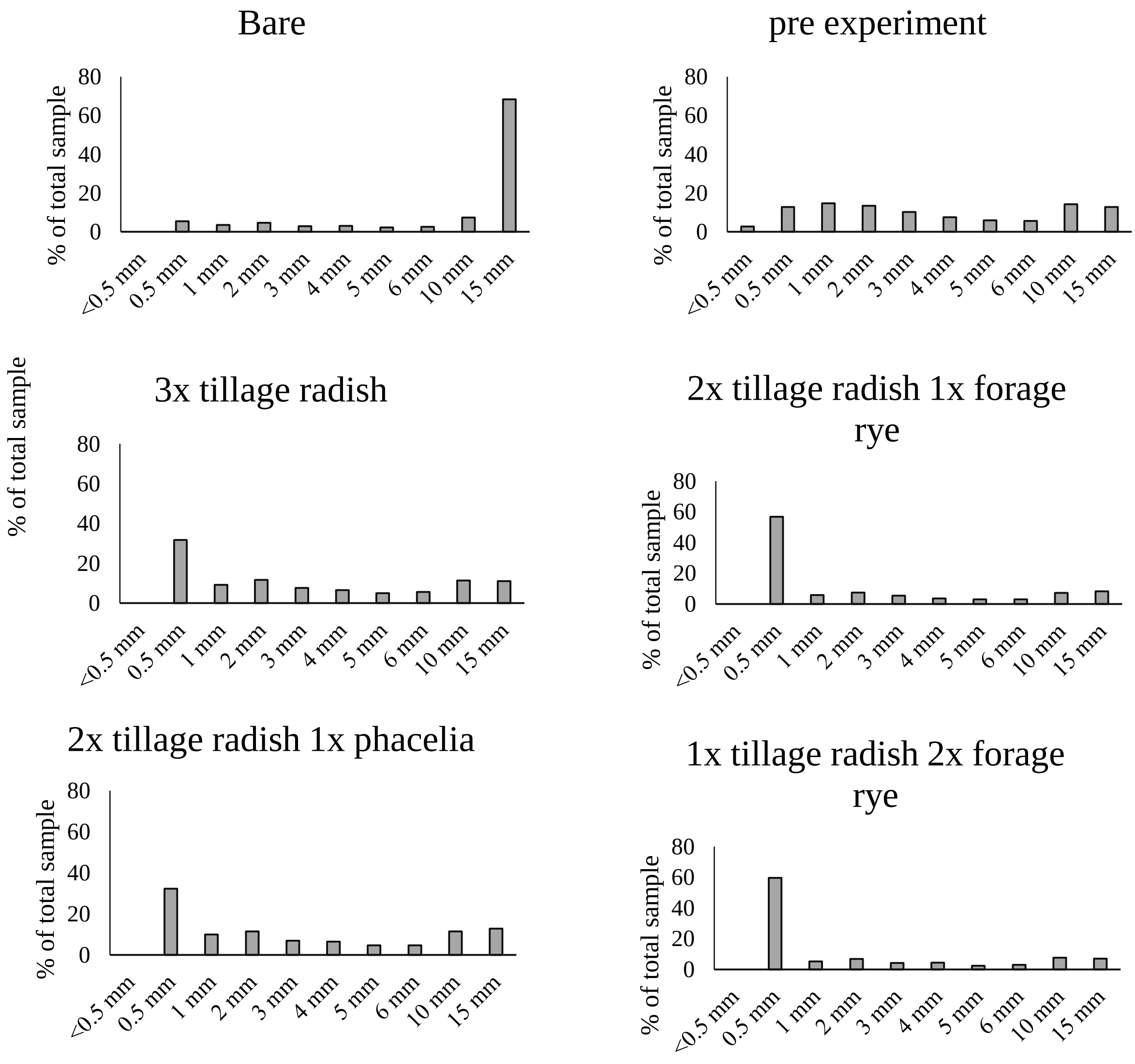


Figure 2.7 Linear regression between number of phacelia plants in each pot and shoot biomass (*P<0.001*) d.f 49.

2.3.2 Soil structure

2.3.2.1 Aggregate size distribution

Soil prior to the experiment (See pre-experiment) shows an even distribution of aggregates between each diameter class (Fig. 2.4). The bare soil treatment showed that this distribution had developed with a majority of aggregates >15mm. In comparison TTF, TFF, TPP, FPP and FFP all showed an increase in aggregates smaller than 1 mm in diameter. TTT, TTP and FFF however resulted in an aggregate size distribution more similar to the soil prior to the experiment which had a more even aggregate size distribution.



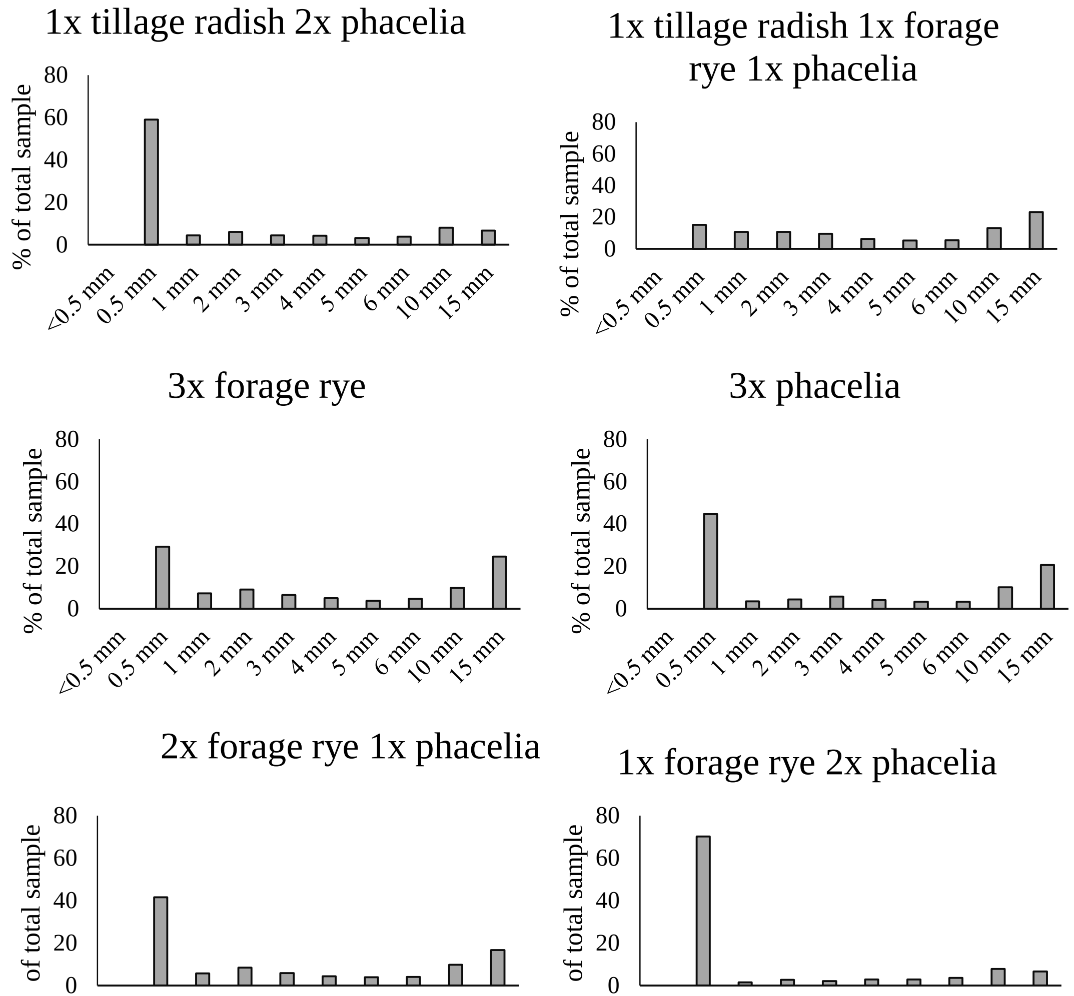


Figure 2.8 Aggregate size distribution at the start of the experiment, and bare soil and the cover crop mixtures (Table 2.11)

2.3.2.2 Mean weight diameter and coefficient of uniformity

Figure 2.5 shows mean weight diameter following the different cover crop treatments. Bare soil had the largest mean weight diameter. This was not significantly different to FPP, PPP, or FFF. FPP, PPP and FFF were not significantly different to FFP, TFP or TFF however they had significantly larger MWD to TTT, TTF, TTP and TPP which had the smallest mean weight diameters measured (*P=0.002*).

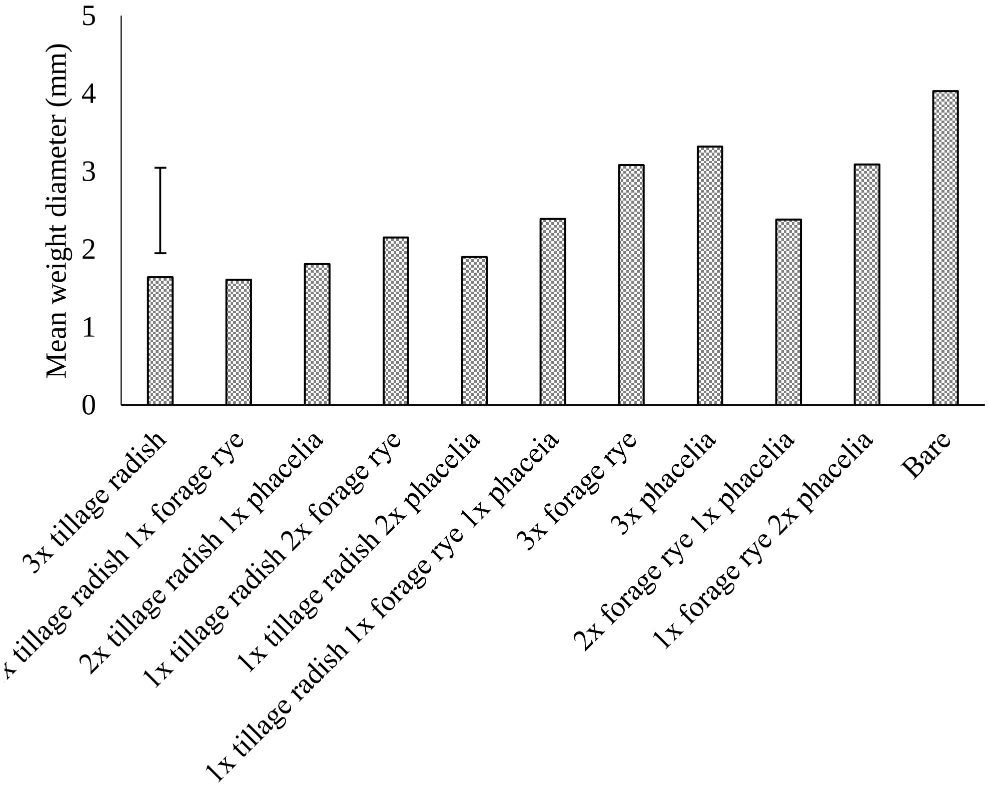


Figure 2.9 Mean weight diameter of experiment showing significant differences between treatment (*P=0.02*, d.f 26). Error bars show LSD of 1.31.

.

2.3.2.3 Bulk density

No significant differences in bulk density were observed between the cover crop treatments. However, a linear relationship between mean weight diameter and bulk density was observed (*P=0.028* Fig.2.6) suggesting that as soil bulk density diameter increases so does mean aggregate weight. Furthermore, there was a significant positive relationship between soil moisture and MWD (Fig.2.7)(*P<0.001*).

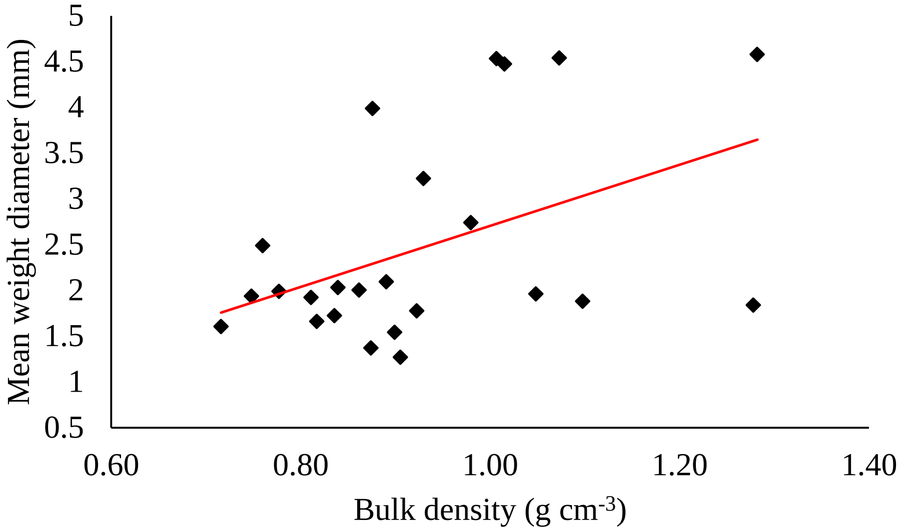


Figure 2.6 Significant regression between soil mean weight diameter and soil bulk density (*P=0.028*, d.f 23, $R^2$0.19)

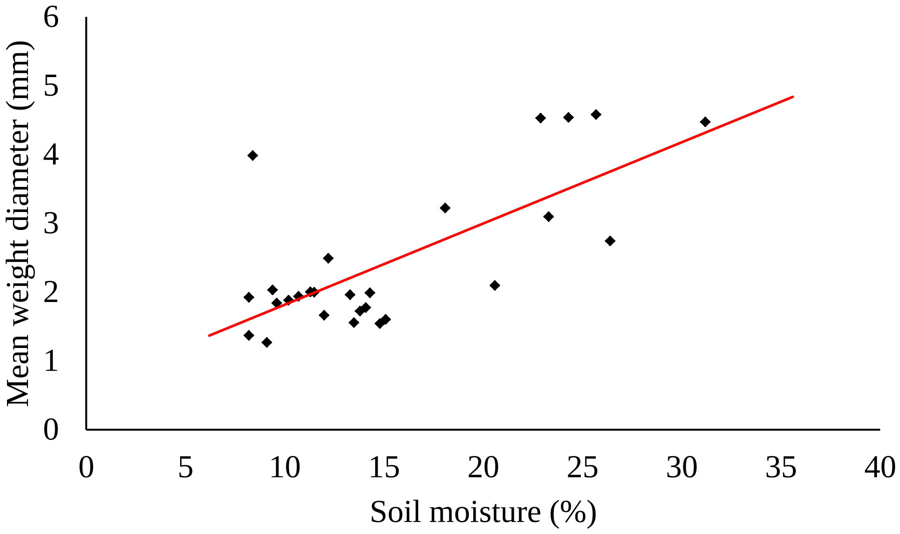


Figure 2.7 Significant regression between soil moisture and mean weight diameter of the aggregate size distribution (*P<0.001*, d.f. 26, R^2 0.511).

2.4 Discussion

2.4.1 Cover crop growth

Treatments containing tillage radish (T) and/or forage rye (F) produced significantly more above ground biomass after 700^{o}C days than the treatments containing *Phacelia* (P) or a combination of phacelia and forage rye. Similar results have been seen in the field conditions by Van Dam and Lantinga (1998). This suggests tillage radish and forage rye are capable of producing large quantities of biomass when grown in monoculture or in combination and therefore there does not appear to be a negative effect caused by interspecies competition. Phacelia produced the same quantity of biomass grown in monoculture as when grown with forage rye. The only difference in the biomass production of phacelia treatments was with the TTP treatment where biomass production was significantly greater than PPP. Reviewing the other treatments it appears that this increase in biomass is as a result of radish producing most of the biomass. This is further illustrated when comparing biomass of the treatments TTP, TPP and PPP as the biomass produced slowly decreases when the treatment moves from majority being made of tillage radish to being solely phacelia. The treatment TFP produced the same amount of above ground biomass as the treatments in the larger group with suggests that there are no negative consequences of growing the species in a three way combination.

2.4.2 Responses of cover crops to combining species

There is no evidence of a benefit of the combination treatment, in terms of biomass production. In some situations around the world it has been shown that using combinations of species can result in overall increases in crop biomass production Liu et al. (2018). Intercropping assumed that combining species can have a favourable land equivalent ratio (LER) meaning crops have a lower land requirement when grown in combination than in monoculture. For example it has been found that intercropping can have benefits to crop biomass production for bioenergy crops (Hallam et al., 2001). Liu et al. (2018) has attributed yield benefits of field crops such as maize (*Zea mays*) and soyabean (*Glycine max*) to greater radiation use efficiency when the two crops were combined. However, Liu et al. (2018) explained that yield increases were only found when species were grown in separate strips and in optimum row spacing. This suggests that to see benefits to growing species combinations work needs to be done to understand the optimum spatial arrangement of the different species.

2.4.3 Cover crop growth in response to wider environmental conditions

The experiment was conducted in conditions more favourable than typical field conditions. Daytime temperatures in the glasshouse were considerably higher than field conditions and therefore thermal time was accumulated much faster than the case in a typical UK autumn. This is likely to have resulted in faster growth of the forage rye and phacelia which went into reproductive growth and produced an inflorescence which would not normally occur in the field. Furthermore, brassica cover crops have been reported to have greater leaf turnover than forage rye or phacelia. Etheridge et al. (1998) showed senescence of radish leaves occurred after approximately 478^{o}C days compare to 598^{o}C days for forage rye suggesting that even if radish produced a greater number of leaves over time, this would not be reflected in biomass as radish leaves senesce more rapidly than rye. Therefore if cumulative biomass had been taken, the biomass produced from treatments containing tillage radish are likely to be greater than recorded. It is important to note that leaf senescence is highly linked to environmental conditions such as temperature and light quality particularly as cover crop species tend to be used during the autumn and winter months where temperatures are low and light quantity is poor.

2.4.4 Relationship between cover crop growth, soil moisture and soil aggregation

The relationship between above ground biomass and soil moisture content strongly suggests that treatments with more above ground biomass have greater water demand. It is likely that this will dry the soil out to a greater extent. In turn the drying effect is likely to influence the soil structure, potentially resulting in crack formation, smaller aggregates, and a structure which is less likely to be altered by external pressure. This has been measured in many other situations and is likely to be as a result of larger leaf biomass having a greater demand for water for use in photosynthesis (Monteith, 1986). As water is lost through the stomata of the plant, more is drawn up from the roots, resulting in lower soil moisture content. However, it is possible that this relationship will have been exacerbated as a result of glasshouse conditions being conducive to high transpiration rates.

In contrast to this experiment, it has been suggested by Van Dam and Lantinga (1998) that in field conditions forage rye produces a larger amount of shoot biomass than brassica cover crops. Laine et al. (1993) showed that brassica cover crops adopt a root growth pattern that lends itself to heavily exploiting a relatively small area of soil for water and nutrient uptake compared to cereal cover crops which adopt a more extensive proliferation, taking up water and nitrogen from a larger area. Van Dam and Lantinga (1998) found that in cool, winter conditions rye has been shown to cease transpiration whereas tillage radish can continue to take up water during winter conditions. The findings of Laine et al. (1993) showed that rye exploits a larger area of soil compared to radish and therefore we may not have seen these differences in cover crop growth if the experiment was conducted in autumn field conditions. In field conditions, cover crops are likely to have a lower water demand as cooler temperatures in the autumn result in lower transpiration rates. It is also likely that rainfall events would result in a smaller difference in soil water content. However, this experiment suggests that treatments containing a larger proportion of tillage radish or rye may have a drying effect on the soil. It would be expected that these crops, therefore, would have a greater impact on soil physical properties.

To develop this finding, more detailed measurements of field conditions will be necessary to understand whether this phenomenon translates to field conditions. Field studies have suggested that overwintered cover crops may result in reduced infiltration of water to groundwater and aquifers which may go some way to suggesting that this soil drying effect does occur in field conditions (Allison et al., 1998a). However in the UK it is likely that over-winter rainfall will lead to field capacity being achieved prior to sugar beet drilling (Allison et al., 1998a).

The distribution of MWD suggests that treatments with a high proportion of tillage radish may shift the distribution of aggregates to lower aggregate diameters. There are two possibilities for the cause of this. The first may be that tillage radish roots are able to cause ‘active’ soil aggregation through the production of root mucilage which increases aggregate stability and prevents the formation of macro-aggregates or ‘clods’. Several studies have established a clear link between cereal roots and the production of root mucilage useful for increasing aggregate stability. However this relationship is not well established with tillage radish suggesting that it is unclear whether it is the case in this experiment (Liu et al., 2005, Martins et al., 2009). The second possibility is that, by extracting moisture from the soil, the plants have prevented the soil from slumping. Where the bare soil treatment received consistent amounts of irrigation without plant growth, the soil had a greater proportion of macro-aggregates which in turn resulted in a larger MWD and a smaller coefficient of uniformity (C_u). Figure 2.6 shows that as soil moisture increases the mean weight diameter increases. This appears to be a much better explanation for the reduction in mean weight diameter than root mucilage causing aggregation of soil particles. In comparison to the bare soil treatment, the treatments with a low mean weight diameter have been able to segregate, in preventing slumping and clod formation, rather than to aggregate it into firm particles.

There were no differences in bulk density between the cover crop treatments. This was not surprising as there were no compaction treatments introduced into the experiment. We were able to demonstrate a positive linear relationship between mean weight diameter and bulk density. This suggests that soil with a larger proportion of small aggregates is likely have a greater macro porosity. Similarly, the growth of roots will have contributed to the production of a more connected pore space that contributes to water and air movement through the soil. This has been seen in a number of studies (Dexter, 1988, Emerson, 1954) and suggests that although no specific treatment effect was observed, there is a link between plant roots, aggregate size and porosity. There is substantial evidence in the literature to suggest that root diameter has a direct effect on pore size distribution suggesting cover crop species with thick roots may be more effective at increasing soil pore connectivity than cover crops producing roots with a narrow diameter.

2.5 Conclusion

There was a clear relationship between cover crop growth, soil moisture and a production of small aggregates. Cover crops that had a higher water use produced an aggregate size distribution with more small aggregates. It was confirmed that different cover crops had different effects on the soil moisture and aggregation but it was not easy to distinguish whether this was an effect of root characteristics, as suggested in hypothesis 1a, or whether it was water uptake by different species. There was suggestion that different cover crop species combinations have varying impacts on the soil structure but it was impossible to confirm that hypothesis 2 could be an accurate summary of their effect. Without measurements of root growth it is impossible to determine whether these differences are driven by rooting traits rather than the wetting and drying of the soil. Nevertheless, if the effect of cover crops on soil aggregation is transferred to field conditions then it is likely that the drying and aggregation effect may prove useful in generating soil structural characteristics that support crop root growth.

Chapter 3: The effect of tillage radish and forage rye on soil structure and sugar beet growth in controlled conditions using metre tall soil columns

3.1 Introduction

Chapter two demonstrated that cover crop growth, in particular tillage radish, resulted in a larger proportion of small soil aggregates. The same trend was seen for forage rye and phacelia although to a lesser degree. This suggests that cover crops, at the small scale, and in controlled conditions do indeed have a significant effect on soil structure. Chapter two focussed on the root effects on a highly restrictive volume of soil and therefore the results may be influenced heavily by the potential for plants to become pot bound. This may result in greater root length densities as soil volume is limiting which may in turn influence soil aggregation. Laine et al. (1993) suggests brassica crops with a single tap root are likely to exploit a smaller area of soil for water faster than cereal cover crops, which tend to produce a more adventitious root system. It is therefore important to continue to investigate whether the ideas set out in sub-hypothesis 1a shows that species rooting characteristics has the greatest influence on the effect of cover crops on soil structure. This suggests that the experimental conditions of Chapter two may allow the tillage radish cover crops to influence the soil moisture content and aggregation of the soil relatively more than the forage rye cover crops in less limiting conditions.

In order to understand the effects of cover crop rooting on soil structure without the soil volume being a limiting factor, a further experiment was devised using the same soil texture as the experiment in Chapter two but using 1m soil columns in order to assess whether, as stated in hypothesis 1f, that the volume of soil used will determine, at least in part, the effects of cover crops on the soil structure. A larger volume of soil is able to more closely resemble field conditions. In addition the experiment was conducted during the autumn and winter months when photoperiod is likely to more closely mimic the normal cover crop growing period. Furthermore, with the removal of soil volume limitations, cover crops species may behave more differently to one another as in the study described by Laine et al. (1993). Following the high density of roots seen in chapter three, this chapter will be a useful comparison when considering sub-hypothesis two and whether combining species will result in a greater effect on soil structure.

This experiment will also offer the opportunity to follow cover crops with sugar beet without disturbing the soil. While this will only be achieved using single plants rather than a large population it should allow for some consideration of sub-hypothesis three to understand the effects of cover crop roots on sugar beet water and nutrient uptake.

3.2 Materials and Methods

3.2.1 Overview

In autumn 2016 the experiment was constructed in the glasshouse. Soil columns with a height of 1 metre and diameter of 15 cm were filled with approximately 18 litres of sandy loam soil. Columns were fully filled to a poured in density, watered and left to slump and then topped up to being full before being watered once again. Soil was allowed to slump, approximately 3 cm, three times over a period of a day for each slump. The following four treatments were used: forage rye (F), tillage radish (T), forage rye and tillage radish (FT) and bare soil (B). In each treatment several seeds were sown (apart from bare soil) which were thinned to two plants per column when seedlings were established.

The four treatments were replicated 10 times to have a total of 40 columns. This was set out in five blocks containing two replications per block. Blocks were laid out to account for a gradient in temperature and light quality. In all the columns the treatments were established and grown from September to January in an unheated glasshouse accumulating approximately 1000 ^{o}C days above an assumed base temperature of 0^{o}C. Columns were irrigated automatically and received 20 mm of water per day. When sugar beet were established in the columns in the second half of the experiment, an equivalent of 1g nitrogen was applied to each sugar beet seedling in the form of ammonium sulphate fertiliser $(NH_4)2SO_4$.

In January, the first half of the experiment was complete and half of the replicates were harvested for soil and root analysis of the cover crops. The plants in the remaining replicates were defoliated by hand and sown with sugar beet two weeks later. The sugar beet were grown for a further two months. After this time analysis of leaf growth was taken before the sugar beet were removed from the columns and measurements of storage root growth were taken. Of the 20 columns that were used to grow sugar beet, four were selected for X-ray Computed Tomography scanning for non-destructive imaging of the plants and soil during cover crop and sugar beet growth.

3.2.2 Measurements following cover crop growth

3.2.2.1 Soil moisture

Measurements of soil moisture were taken from the soil surface of each column using the Delta-t theta probe set to the mineral soil setting. The probe was inserted into the middle of the soil column to the point at which all probe rods were fully inserted in the soil. Care was taken to avoid penetrating radish taproots with probe rods. One measurement was taken from each column due to the limited sampling area.

3.2.2.2 Shear Strength

Immediately after soil surface moisture was measured using the theta probe, a reading of the soil surface shear strength was obtained using the Edeco Pilcon shear vane. Using the 33 mm vane a measurement of the shear strength of the soil between 0-28 kPa was obtained. This figure was not corrected for soil moisture in order to capture the effects of cover crops on soil moisture and reflect the conditions that would be experienced by a root or mechanical equipment that would experience whatever moisture content the soil was at.

3.2.2.3 Cover crop above ground biomass

Leaves were removed from the columns at the point where the plant base met the soil surface, and dried at 70^{o}C until a constant weight was recorded.

3.2.2.4 Soil sampling

The soil columns were opened and marked at depths of 10 cm, 30 cm, 50 cm & 70 cm. At each depth two sections of 5 cm thickness were separated from the rest of the column. The 5 cm slice from above each depth was used for root analysis and the 5 cm slice from below each depth was used for soil analysis.

3.2.2.5 Soil bulk density

From the centre of each of the soil slices, excluding those used for root analysis, a bulk density ring was used to take a sample with a volume of 140 cm3. Samples were weighed immediately after being taken and then dried in an oven at 105^{o}C for at least 24 hours. Samples were then reweighed when dry to get the weight of the sample and the bulk density was calculated in g cm-3.

3.2.2.6 Aggregate size distribution

The remaining soil volume was collected and air dried at approximately 30^{o}C for approximately one week until the soil was no longer losing moisture at ambient conditions. The soil was then passed through a stack of sieves with the diameters 10 mm, 6 mm, 5 mm, 4 mm, 3 mm, 2 mm, 1 mm, 500 µm, 50 µm. Soil on each of these sieves was weighed and then used to calculate a size distribution for the aggregates in each column at each level.

3.2.2.7 Root analysis

The remaining soil sections were washed using the Delta-radish root washer which separated organic matter from inorganic matter. Resulting samples were placed in containers filled with water and stored overnight. Samples were then passed through a number of sieves to separate roots from organic matter by flotation. Clean root samples were placed directly on WinRHIZO trays. All samples were scanned using the WinRHIZO scanner to produce images for analysis using the same software. Following the scanning and analysis, root samples were dried at 70^{o}C until constant and then weighed.

This process was repeated at the end of the second half of the experiment for the sugar beet roots excluding the storage root, which had expanded to a point too large for the scanner system.

3.2.3 Measurements of sugar beet growth

3.2.3.1 Sugar beet leaf measurements

Prior to harvest, SPAD meter readings were taken from the 5th leaf which was the largest fully expanded leaf. Using the Minolta SPAD meter, five random positions of the leaf were measured and the mean value recorded.

At harvest sugar beet leaves were removed from the plant at the point where the petiole joined the crown. Leaves, including petioles, were then passed through the Licor LI-3100C Area Meter to get the total leaf area of the plant. In addition, the length of the leaf petiole from the plant crown to the point where the leaf lamina expands was measured. Leaves and petioles were then dried at 70^{o}C until a constant weight was achieved. Above ground biomass samples were then milled for total nitrogen analysis using the DUMAS system (Sweeney and Rexroad, 1987).

3.2.3.2 Storage root

When leaves had been removed from the plants the remaining storage root was removed from the column and separated from the lateral roots. Each storage root was washed, weighed and then sliced to aid the drying process. The root was then dried at 70^{o}C for approximately three weeks when there was no water left in the root. The samples were then reweighed for storage root dry weight.

3.2.3.3 X-ray Computed Tomography

Four soil columns were scanned twice during the experiment. Initially the columns were scanned the day before cover crop harvesting. The second scan was completed the day before to the sugar beet harvest. The columns were scanned using a VTomex scanner by GE Inspection Systems at the University of Nottingham Hounsfield Facility, Sutton Bonington Campus. The resolution of the scans was 150µm.

3.2.3.4 Image analysis of scans

Reconstruction of the scanned images was done using the software Volume Graphics 2.2 and information collected from the scans focussed around the growth of cover crop and sugar beet roots and the areas of the columns which experienced changes in porosity. No statistical analysis of the scanned images was carried out due to lack of replication. Pore space was thresholded from black and white images manually as determined by the visual differences between pore space and soil matter.

3.2.4 Statistical analysis

Statistical analysis of the experiment was carried out using GENSTAT 19th Edition. General one way ANOVA was used for the majority of analysis with the exception of repeated measures ANOVA which was used to analyse root length density using column depth as the repeated measure. For both types of ANOVA when statistical significant differences were present Genstat was used to automatically calculate the LSD using the Fisher method (1935). Means The LSD was used to present an error bar showing the smallest significant difference between any treatments for comparison using a single error bar.

3.3 Results

3.3.1 Conditions following cover crop growth

3.3.1.1 Soil moisture

Columns containing bare soil had a significantly higher water content at 5 cm depth than all other treatments (figure 3.1, P<0.001). There were no differences between treatments containing cover crops.

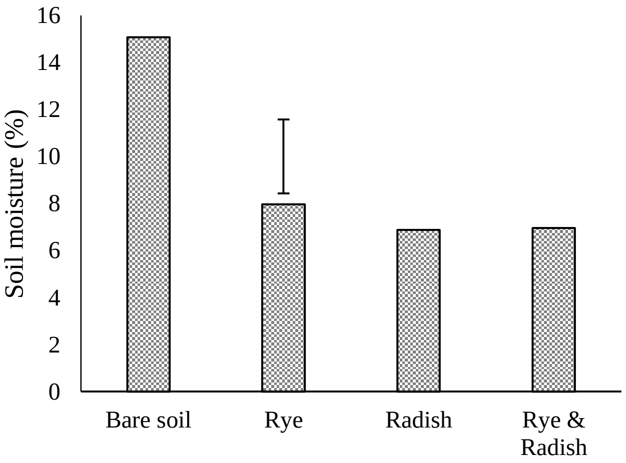


Figure 3.10 Soil moisture content of columns at harvest of cover crops (*P<.001,* 39 d.f.) Error bars depict LSD of 3.14.

3.3.1.2 Cover crop biomass

No differences in cover crop biomass were recorded in the experiment when bare soil was excluded (*P=0.533*). The overall mean of cover crop treatments biomass was 33.3 g.

3.3.1.3 Shear strength

Shear strength was significantly higher in rye and rye & radish treatments than bare soil or the radish only treatment (Fig.3.2, *P<0.001*). There were no differences in shear strength between the bare soil and radish treatments which had mean shear strengths of 10 kPa, nor were there differences between treatments containing rye which had a mean shear strength of 16 kPa.

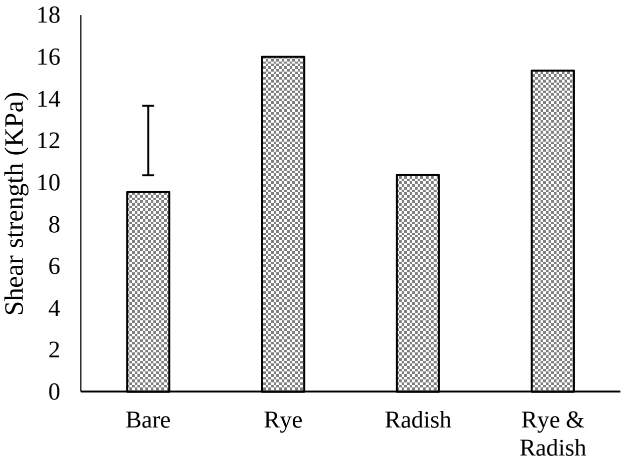


Figure 3.11 Mean shear strength of soil surface of columns at cover crop (*P<0.001*) Error bar shows an LSD of 3.314.

3.3.1.4 Aggregate size distribution

No significant differences in aggregate size distribution were found at any of the depths sampled (Fig. 3.3). However, at all depths there was a trend for more in large aggregates in the bare soil treatment compared to columns containing cover crops. This can be seen particularly clearly with the 6mm aggregate class.

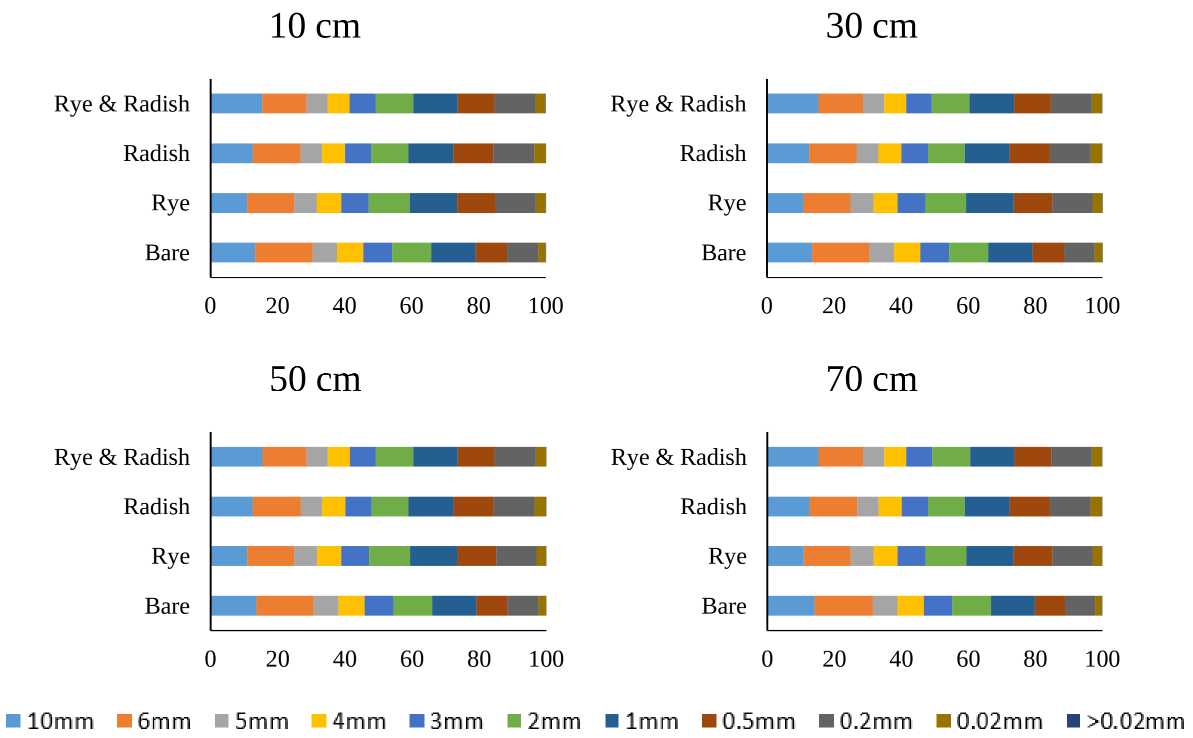


Figure 3.12 Mean aggregate size distribution for the four depths of the columns. No significant differences between treatments

No differences in mean weight diameter (MWD) were recorded between treatments when they were analysed as discreet treatments. When cover crop treatments were combined and analysed as cover crops against bare soil, the two groups were significantly different to one another (Fig. 3.4, *P=0.05*).

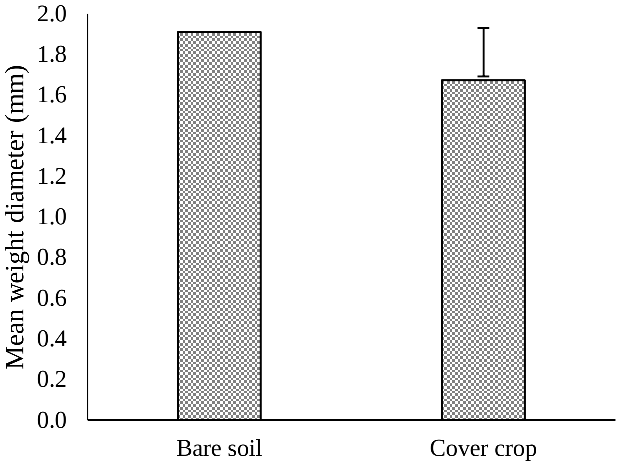


Figure 3.13 Mean weight diameter of aggregate size distribution where cover crop treatments have been combined. Repeated measures ANOVA of all depths (*P=0.05*), d.f 14. Error bar LSD of 0.239.

3.3.1.5 Soil bulk density

Bare soil, rye and radish were not significantly different from one another. Radish and rye & radish were not different to one another. Rye & radish showed a lower bulk density than bare soil and rye (Fig.3.5). There appeared to be a trend for treatments containing radish to have a lower bulk density than those that did not. This may reflect the changes to porosity as a result of the

Figure 3.14 Mean bulk density of columns through all depths. (*P=0.05*, d.f. 39)

large radish taproot.

3.3.1.6 Root growth

There were no differences between treatments in root length density (RLD) (Fig. 3.6) but in all species RLD increases with depth (*P=0.008*). There appeared to be a trend for reduced root length density where the rye and radish plants were combined. In the levels 10 cm, 30 cm, 50 cm there appeared to be a reduction in root length density of rye & radish compared to the treatments that were only single species.

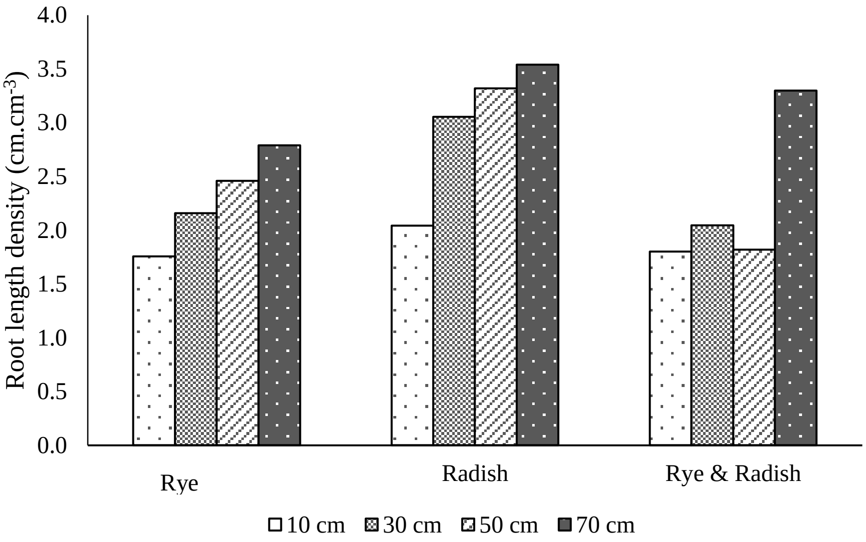


Figure 3.15 Root length density of cover crops at each depth. (*P=0.008*). Error bar shows LSD 1.32

3.3.1.7 X-ray Computed Tomography

Figure 3.7A and 3.7B show the cross section, from above of bare soil and rye treatments respectively. No roots were visible due to the difficulty capturing roots < 5 mm in diameter. In Figures 3.7A and 3.7B pore space appears to be evenly distributed across the whole region. Figures 3.7C and 3.7D show that where the radishes have grown the size distribution of the pores has changed.

There appeared to be fewer small pores resulting in a less even distribution of pore space as shown by the apparent increase of connected soil pores. However, the area immediately surrounding the radish taproots shows large cracks and fissures where the soil has cracked laterally under the force of the swelling radish taproot.

In addition to the visual changes to pore size distribution, the CT images also suggest that root growth in treatment radish & rye was not affected by one another. Nor does there appear to be an aversion of rye roots to radish or vice versa.

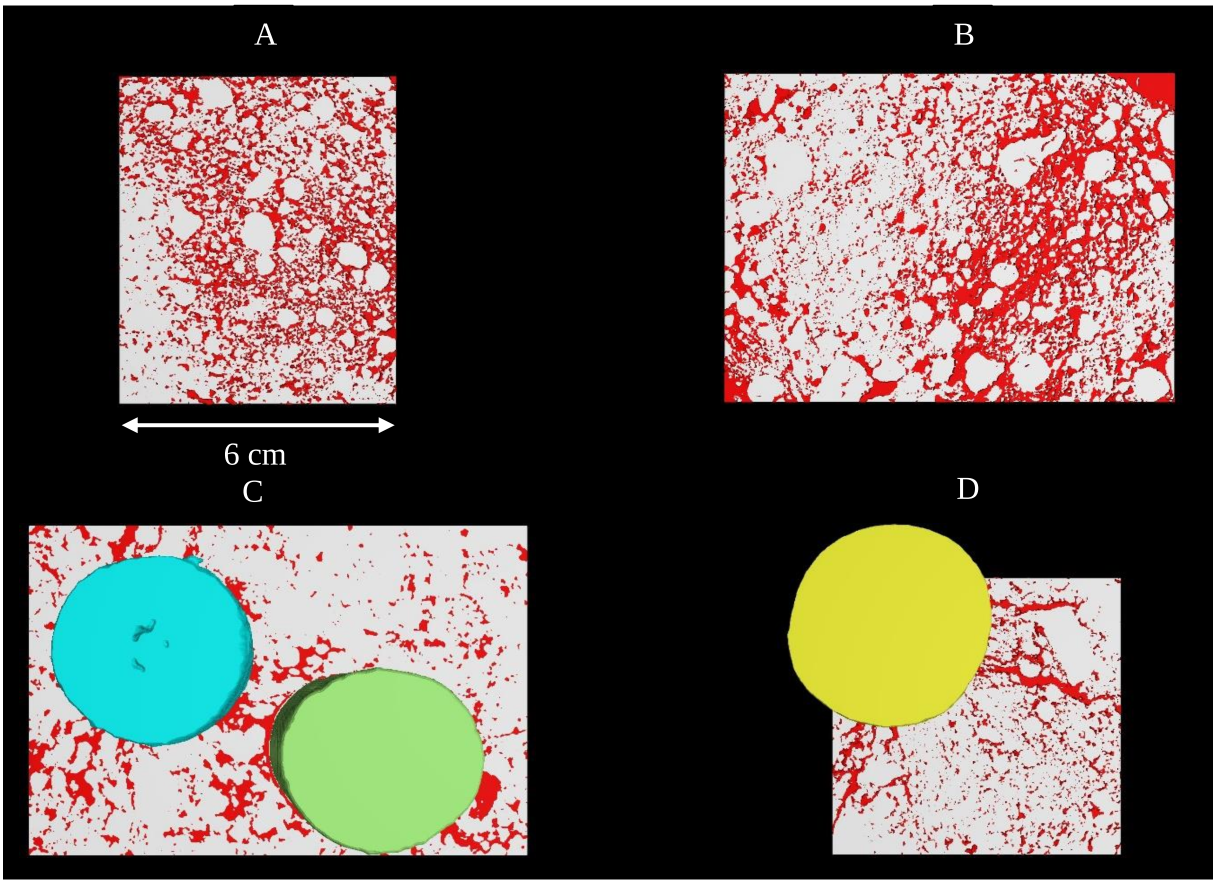


Figure 3.16 Cross sections at 10 cm depth of soil columns before termination. A) Bare soil B) Rye C) Tillage radish D) Rye & tillage radish. White shows soil, red shows pore space and coloured areas show radish roots

3.3.2 Sugar beet growth

3.3.2.1 Leaf chlorophyll (SPAD)

Figure 3.8 shows the differences between treatments in the SPAD values of leaf five at the point where this was the largest fully expanded leaf. Sugar beet following bare soil, radish and rye & radish had significantly higher SPAD values than sugar beet following rye.

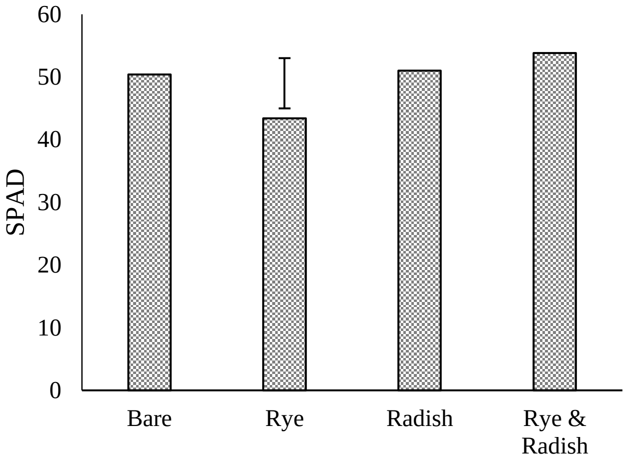


Figure 3.17 SPAD of sugar beet 5th leaf at full leaf expansion (*P=0.042*) error bars show LSD of 7.

3.3.2.2 Sugar beet leaf area

Sugar beet following bare soil produced the largest leaf area with an average of 4000 cm^2 per plant (Fig 3.9). Sugar beet following rye had significantly higher leaf area than sugar beet following radish and rye and radish. Treatments rye, radish and rye & radish had means of 3272, 2756 and 2576 cm^2 respectively.

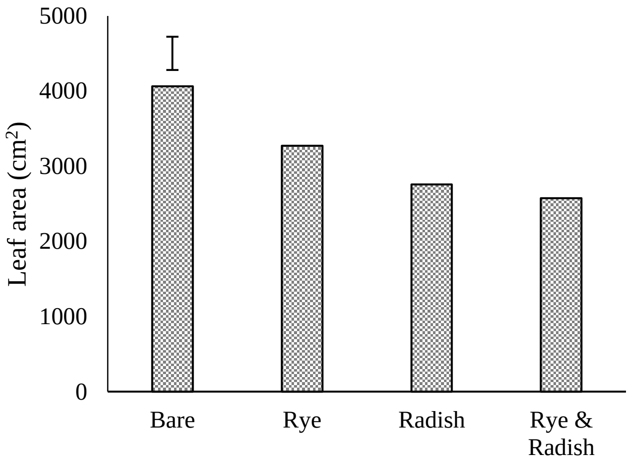


Figure 3.18 Sugar beet leaf area at harvest following different cover crop treatments (*P<0.001*) error bar shows LSD of 440.

3.3.2.3 Leaf nitrogen content.

Sugar beet following bare soil had significantly higher nitrogen content than all other treatments (Fig.3.10)(*P<0.001*). Sugar beet following rye & radish showed the lowest nitrogen content however this was not significantly different to sugar beet following radish alone. Sugar beet following rye showed a significantly higher nitrogen content than rye & radish but not sugar beet following radish on its own.

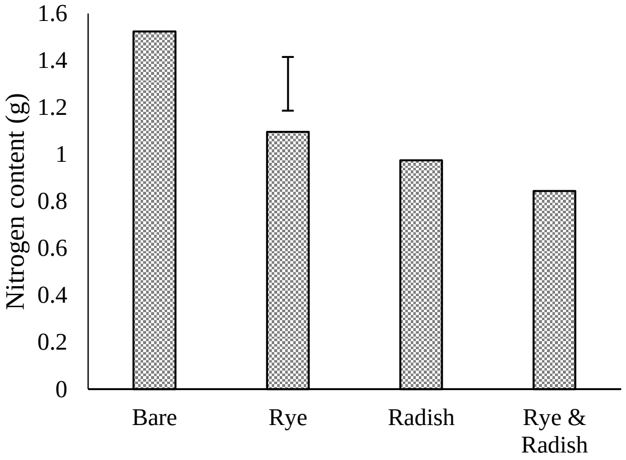


Figure 3.19 Mean total nitrogen content from above ground biomass of sugar beet following cover crop treatments. (*P<0.001*) Error bars showing LSD of 0.2277.

There was a significant linear relationship between nitrogen content of the above ground biomass and the leaf area of sugar beet (Fig.3.11).

Regression analysis showed that there was no significant (*P=0.381*) relationship between the SPAD of the 5th leaf and the final nitrogen content of the leaves. There was also no significant regression between the SPAD of the 5th leaf and sugar beet taproot fresh weight (*P=0.563*).

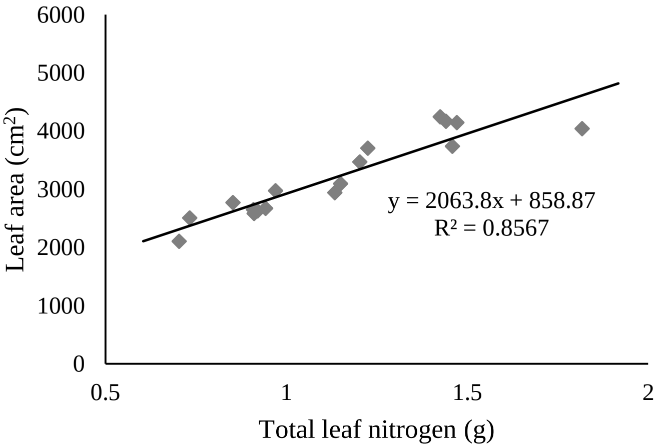


Figure 3.20 Regression between total leaf nitrogen content and leaf area of sugar beet (*P<0.001*).

3.3.2.4 Sugar beet root growth

Bare soil produced significantly larger tap roots than those following rye and radish individually but were not significantly different compared with those following rye & radish combined. Rye & radish produced beet that were significantly larger than sugar beet following rye but there was no significant difference to sugar beet following radish alone (Fig. 3.12).

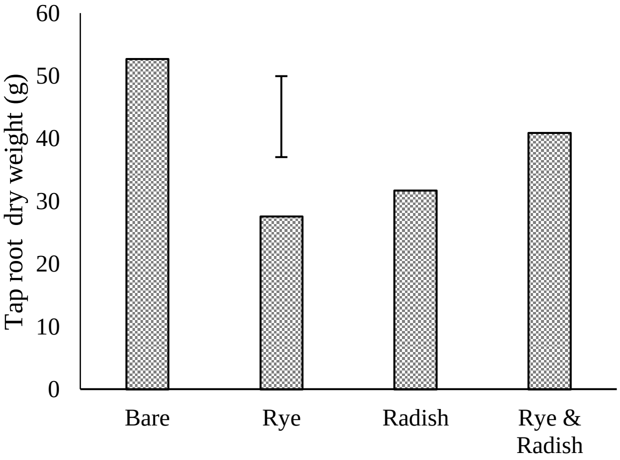


Figure 3.21 Taproot dry weight of sugar beet following different cover crop species (*P=0.005*) Error bars showing LSD of 11.92.

Regression analysis showed a significant positive relationship between leaf area and taproot dry weight ($P<0.001$) although an R^2 of 0.346 shows a large amount of variation in the data (Fig.3.13).

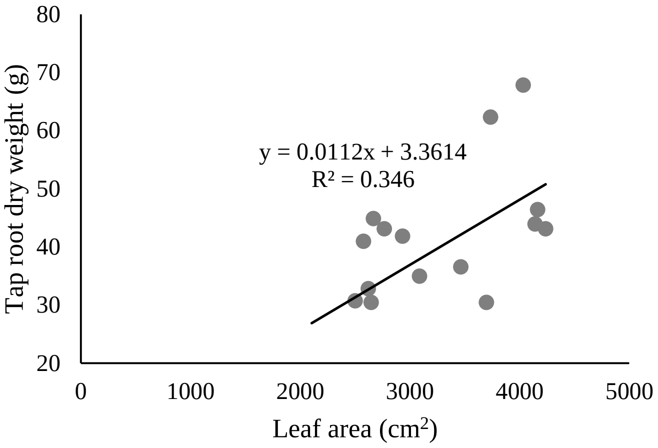


Figure 3.13 Regression between total leaf area and taproot dry weight (*P<0.001*)

Repeated measures ANOVA did not reveal any differences in lateral root growth of beet following the different cover crop treatments. There were differences (*P<0.001*) between roots in the 10 cm layer compared to the deeper soil layers however this was the case for all four treatments. Lateral root length density appeared to be greater in the 10 cm layer following treatments that contained at least one radish plant (Fig. 3.14).

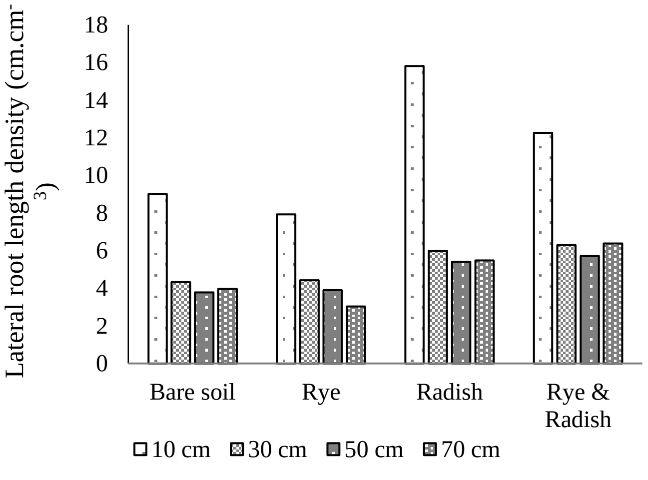


Figure 3.14 Root length density of sugar beet at subsequent depths

3.3.2.5 Shoot to root ratio

Shoot to root ratio was significantly different between treatments (Fig.3.15). Sugar beet following rye produced significantly greater shoot:root ratios than all other treatments. Sugar beet following bare soil and tillage radish alone produced the same shoot:root ratio. There was however no significant difference between sugar beet following bare soil and the rye & radish combination.

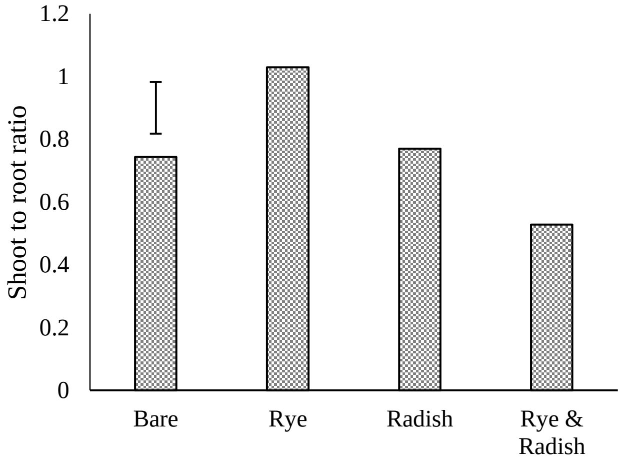


Figure 3.22 Shoot to root ratio of treatments (*P<0.001*). Error bars show LSD of 0.1641

3.3.2.6 X-ray Computed Tomography

CT imagery revealed that sugar beet following bare soil resulted in a storage root shape that was unfanged, straight and deep growing (Fig 3.16a). This suggests that the sugar beet root was not restricted at any point during its growth. Figure 3.16B shows the sugar beet growth following rye had a similar root structure with only slight deviations to the straight growth that was achieved after the bare soil. In comparison, Figures 3.16c and 3.16d show the storage root growth after treatments containing radishes. It is clear that the sugar beet following the tillage radish treatment has appeared to experience restricted growth as reflected by the shape of the storage root in the top soil followed by the tubular growth of the root as it grows between the two radish tap roots at depth. The same effect to a lesser degree is visible in Figure 3.16d where the sugar beet appears to have preferentially grown away from the radish tap root in favour of the unrestricted area where the rye plant was growing.

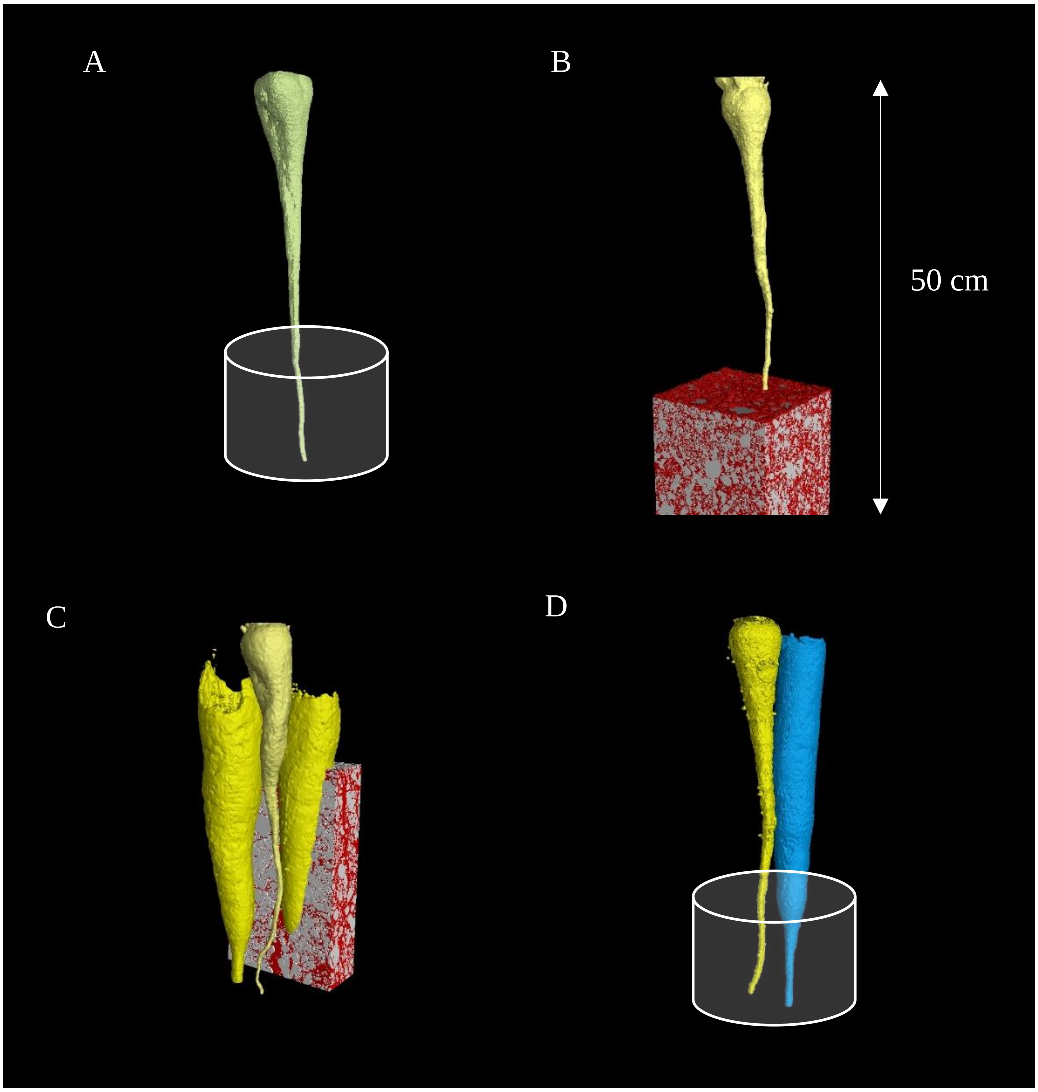


Figure 3.23 X-ray CT reconstructions of sugar beet growing following each cover crop treatment. A) Bare soil B) Rye C) Radish D) Rye & radish.

3.4 Discussion

3.4.1 Soil conditions at cover crop termination

At the point of cover crop termination, soil moisture content was significantly lower in treatments containing plants compared to the bare soil, which is expected due to transpiration by the plants. Unlike Chapter 2, there were no differences between the cover crop treatments. This suggests that the water usage from each treatment was similar and independent of species and that irrigation was sufficient to maintain soil moisture close to field capacity. It is possible that in field conditions cover crop species may have different transpiration rates to one another. Differences in transpiration rates will lead to differences in soil moisture. Previous work has shown that brassica species are able to transpire and continue to grow at lower temperatures that cereal species (Laine et al., 1993).

Bare soil and radishes resulted in a significantly lower shear strength than rye and rye & radish. Using the X-ray CT scans of the soil columns prior to cover crop destruction there is an area of soil between the taproots of the radishes which clearly fractured. It is likely that growth of the taproots has fractured the soil, hence reducing the shear strength. This also may explain why there were no significant differences in soil bulk density between cover crop treatments. Although there were differences in the shear strength, the area was taken up with mostly radish roots. While this will increase the shear strength, as the soil and the root will cause impedance it is unlikely to contribute to soil bulk density from samples as roots are mainly water. Therefore, this highlights the difficulty of getting accurate readings from such a limited sample area. It has been shown previously that high shear strength and low bulk density in the seedbed are detrimental to sugar beet establishment and seedling growth (Koch, 2009). Soil restrictions at depth are likely to result in poor sugar beet root growth. If radish roots were able to fracture and produce more connected pore space at depth the soil may become less constraining to sugar beet growth.

The relationship between bulk density, shear strength and sugar beet emergence has been linked to poor seed-soil contact which suggested that mild compression of the soil, which increased bulk density, had a positive impact on sugar beet establishment (Arvidsson et al., 2012). Establishment is also affected by the soil aggregation of the seedbed. A large proportion of aggregates between 1-3 mm diameters have been linked to good seed-soil contact (Atkinson et al., 2007, Blunk et al., 2017). Seedbeds with a large proportion of aggregates smaller than that have been linked to capping of the soil surface. Similarly, sugar beet are seriously restricted by aggregates that have a diameter of more than 10 mm (Durr and Aubertot, 2000). No differences in aggregate size distribution were found between treatments which contrasts with the results from Chapter 2. It is clear that there were no differences in aggregate size distribution when comparing the discreet treatments. However, there was a trend that soil after cover crops overall had a lower MWD after bare soil compared with cover crop treatments. This suggests that although the cover crop species did not cause specific differences that reflect the individual species, the presence of root growth in the soil resulted in a lower mean weight diameter. A similar relationship was seen in Chapter 2 and has been seen in a number of studies (Gyssels et al., 2005, Roldan et al., 2003, Layton et al., 1993). It is possible that the differences in aggregation may have been more pronounced if the cover crop roots had been more restricted as in Chapter 2. Given that the conditions in the glasshouse during this experiment would have been more representative of cool autumnal conditions, there was a slower growth rate and a lower transpiration rate leading to less extreme wetting and drying cycles. As a result, the soil did not experience the same intensity that lead to such pronounced differences in Chapter 2.

3.4.2 Growth of the cover crop during the autumn

There were no differences in RLD between cover crops but in all treatments RLD increased with depth. Despite all treatments showing the same response, this is not what was expected in terms of root growth. Normally, root length density would decrease with depth as plants will colonise the soil profile starting at the soil surface and working downwards, as seen in the sugar beet. Bodner et al (2010) showed that different species produce roots at different depths, rye for example is more likely to produce an even RLD with depth compared to radish which is likely to proliferate more in the shallow layers before tapering off at depth. Root exploration has been linked to roots growing preferentially towards a water gradient or nutrient gradient (Bao et al., 2014). Furthermore it is well established that roots will follow the path of least resistance (Bengough and Mullins, 1990). It is unusual for plants to invest in root growth in deeper layers compared to shallow layers, close to the soil surface. Initial thoughts were that roots have explored as a result of decreased soil bulk density or increased soil moisture however no relationship was found between either of those factors and root growth. This was confirmed as depth increased in soil columns so did bulk density due to the overburden pressure of the soil (Bachmann and Hartge, 2006). Due to the overall bulk density of the soil in columns being very low, it is possible that the increase in soil bulk density at depth actually reached an optimum point for root growth allowing better root:soil contact. This phenomenon has been seen in work by Hakansson et al. (1988), and Atkinson et al. (2009) suggest that roots respond positively to a level of resistance that promotes root growth.

Radish and rye & radish produced a significantly greater amount of root biomass than rye alone in the 10 cm soil depth. This takes into account the large radish taproots that despite having a relatively low root length density, will contribute greatly to the size of the radish root system. This is a tapering effect of the radish taproot which can be seen. It is possible that this is as a result of the differing root behaviours of rye and radish. Where radish is more likely to explore a small volume of soil with a much greater quantity of roots, rye is more likely to extensively colonise the soil in order to prepare for a adventitious root growth habit as seen in many cereal crops (Laine et al., 1993).

While there were no significant differences, there was a trend for the rye & radish treatment to have the lowest root length density. This might be a result of allelopathic effects of rye (Jane and Putnam, 1986) or interspecies competition. However, when looking at this data in combination with the root biomass it appears that this is not the case. Rye produced significantly greater amounts of root biomass than rye with rye & radish being the intermediate treatment. The production of root biomass by rye and rye & radish is a result of the tillage radish plant in the column. The radish taproot accounts for an extremely large amount of biomass as a result of the large radius despite relatively short length. This confirms that the growth habits of the two species are extremely different and although it appeared that root growth may not be optimum in the rye & radish treatment.

Despite the lack of replication, CT scans of the sugar beet reveal the differences in soil structure as a result of the cover crops. The bare soil treatment shows a relatively even distribution of pores through the lateral section of the soil column. This is because there hasn’t been any influence of roots on soil porosity. Comparing this to the column containing two rye plants and little difference is seen. It is likely that the lateral branching roots of rye will move between soil aggregates within soil pores. As rye roots do not swell to a diameter more than 5 mm it is unlikely that soil will be compressed around the roots particularly as the root biomass was relatively low in comparison to treatments containing tillage radish. The radish treatment resulted in a much lower volume of macropores as seen when comparing the red areas to the bare soil treatment. What was noticeable is that the pore space that is present is mostly attributed to the cracks in the soil which have been borne out of the swelling of the radish roots. This shows that the thick radish taproots cause fracturing through the soil. It is also important to note that this compression of the soil also reduced the amount of smaller macropores as seen by Dexter (1987), and Helliwell et al. (2019). Therefore, despite no overall change in bulk density being measured, it is likely that following tillage radish there are areas of extreme compression and areas of extreme porosity unlike the bare soil or rye treatments which had a more even pore distribution.

3.4.3 Growth and yield responses of sugar beet to cover crops

Sugar beet following rye had a significantly lower SPAD readings. SPAD is related directly to nitrogen content and hence this finding suggested that the sugar beet following rye had a significantly lower nitrogen content. This may have been as a result of nitrogen 'lock-up' as a result of the C:N ratio of decaying rye roots (Hill et al., 2016). It has been reported that as rye decomposes it often requires excess nitrogen from the soil in order to break down. There is the potential for reduced nitrogen availability to result in sub-optimal crop growth and lower yield. However, there was no significant relationship between nitrogen content at harvest and SPAD of the 5th leaf.

Considering leaf nitrogen content at sugar beet termination, there were no differences between cover crop treatments further suggesting that rye did not cause lock up of nitrogen compared to other treatments. However, sugar beet following bare soil had a significantly greater nitrogen content than treatments containing cover crops. This suggests, that following the cover crops, less nitrogen was available for the sugar beet to take up from the soil. It is unclear whether this is as a result of nitrogen being removed by the cover crop plants or whether decomposition of the cover crop roots had caused a lock up effect of the nitrogen. The equivalent of 1g of nitrogen per plant was applied to the sugar beet during early growth. All treatments resulted in a nitrogen content of above 0.9 g per plant suggesting that none were limited in terms of nitrogen supply. Bare soil however had a nitrogen content of approximately 1.5g per plant which is 50% higher than the mean of the cover crop treatments. It is possible that the soil following the cover crops had less available nitrogen than the bare soil treatment. In field conditions it has been seen that cover crops are highly effective at removing nitrate from the soil in the autumn (Cooper et al., 2017) therefore it is possible that the cover crops would have reduced the nitrogen availability compared to the status of the soil prior to the experiment. Cooper et al. (2017) found bare soil in field conditions led to very high leaching of nitrogen. It was expected that the irrigation of the bare soil treatments throughout cover crop growth would result in soil nitrogen loss through leaching. However, it appears that the low intensity of irrigation rather than high intensity of field scale rainfall events has resulted in greater nitrogen availability to the sugar beet that followed, particularly as cover crop leaf biomass was removed for analysis. Furthermore, the warming effect of the glasshouse on the soil after cover crop destruction may have allowed nitrogen to be mineralised resulting in greater quantities of nitrogen being available. This may explain the differences been seen in leaf nitrogen content.

The role of nitrogen in sugar beet has been established to be essential for production of the crop canopy. PAR interception by the crop canopy is directly related to sugar production in the storage root (Scott and Jaggard, 1993a). However, indefinitely increasing nitrogen supply does not result in increasing sugar yields. Milford et al. (1988) found that excess supply of nitrogen results in greater biomass partitioning to the leaf and a reduction in biomass in the storage root. As a result, it has been found the optimum nitrogen application is 120 kg N ha^{-1} (Malnou et al., 2006).

The relationship between plant nitrogen content and leaf area is visible in this experiment. Furthermore there is a significant relationship between canopy nitrogen content and taproot dry weight suggesting that nitrogen was not in oversupply as there was no negative effect on taproot dry weight. However, it is clear that there are discreet differences in taproot size between treatments. Sugar beet following bare soil resulted in significantly larger taproots than rye and radish when grown in monoculture. The rye & radish treatment was not significantly different to bare soil or rye but was also significantly larger than the rye treatment.

The X-ray CT images suggest that the sugar beet following radishes may have experienced restrictions in the soil which prevented the expansion of the sugar beet root. It appears that the taproot has narrowed and been forced to grow in a tubular shape rather than the more typical triangular form. In comparison the rye & radish treatment which only contained a single radish did not cause the restrictions as there was only one of the large radish taproots to compress the soil. It is probable that the confining volume of the column contributed to this meaning compression of the soil was more severe than it would have been in a larger soil volume. It is possible that in field conditions a farmer would allow more time between cover crop termination and establishment of the following sugar beet when the cover crop roots would be allowed to decompose. It is also possible that chemical destruction using glyphosate or grazing with sheep would also hasten the decomposition of the root material. However it is also important to note the potential restrictions to sugar beet growth if cover crops are not properly destroyed which could become a major consideration for sugar beet growers looking to make use of reduced tillage practices.

The reason for the relatively low taproot dry weight of sugar beet following rye remains unclear. Unlike the treatments radish or rye & radish, there were no thick taproots to cause soil restrictions. Furthermore, the sugar beet following rye appear to have a significantly larger shoot to root ratio suggesting that the sugar beet partitioned more biomass towards the leaves rather than the roots. This is a symptom of oversupply of nitrogen which is unlikely as the nitrogen supply was lower than in the bare soil treatment. One possibility for this may be that sugar beet is experiencing negative impacts of the allelopathic compounds released by rye however, looking at lateral root growth, there does not appear to be any difference between treatments in terms of lateral root length density. This also suggests that there are no restrictions to water uptake as all treatments had a very similar root length density at all levels. As yet we have no explanation for this effect of rye on the sugar beet growth.

Burr-Hersey et al. (2017) suggested that tillage radish cover crops may be effective at removing compacted layers from soil which may remove restrictions for following crops. The fracturing effect of the tillage radish has also been seen in this experiment however, it appears that tillage radish root growth can also be detrimental to the growth of the following crop if the taproot has not decomposed. Nevertheless, if decomposition of the radishes had occurred, it is likely that the pore space would have become less evenly distributed. It is possible that the fracturing of soil may be useful when layers of compaction are present however it is also possible that this effect may reduce root growth in non-compacted soil layers if it resulted in more restrictive conditions.

3.5 Conclusions

When grown in large soil columns cover crops were able to alter the soil physical conditions compared to bare soil although the effect was smaller than in pots. This suggests that the volume of soil that the cover crops are grown in will have a considerable effect on root density and their influence on the soil structure. Thus this experiment suggests we should accept sub-hypothesis 1f showing the volume of soil has a considerable effect on soil conditions.

Aggregation of the soil was affected by the presence or absence of plants and did not appear to be as a result of specific cover crop species. This suggests that we ought to reject sub-hypothesis 1a at least in controlled conditions as we have not seen any specific effects of cover crop rooting on soil structure in either of the initial experiments. Significant differences in soil moisture, shear strength and the structure of the pore space as a result of cover crop treatments. However this was only when all cover crop treatments were compared to bare soil suggesting we should also reject sub-hypothesis two as species combination do not appear to enhance cover crop activity on the soil structure.

Sugar beet following bare soil resulted in the best growth of the sugar beet. This may be explained by the nitrogen content of the sugar beet following the cover crops which suggested that they interfered with sugar beet nitrogen content, particularly the rye treatment. However, it is also possible that sugar beet root growth was restricted in columns that contained the radish and rye & radish treatment as a result of soil compression and lack of radish decomposition. This may not have been the case if radish roots had properly decomposed. In this situation it is not possible to accurately accept or reject the ideas set out in sub-hypothesis three that there would be an improvement in sugar beet water and nutrient uptake following a cover crop. Further testing is required in field conditions to draw meaningful conclusions on this hypothesis.

Chapter 4: An assessment of growth of cover crops grown in mono-culture and multi-species combinations in controlled conditions

4.1 Introduction

The final yield of a crop is always dependent of the growth of the crop throughout the season. In most cases, this will mean a period of vegetative growth where the plants develop a strong rooting structure for water and nutrient uptake, at the same time as the production of a large leaf canopy for effective interception of photosynthetically active radiation (PAR). A crop that is able to effectively absorb all nutrients and light is likely to produce a high yield, assuming the absence of disease. This is the same for cover crops with the exception that the ‘yield’ can be thought of as the benefits that the cover crop is being used to gain.

This chapter is aimed at investigating the effects that specific cover crop species have on the growth of one another. It is most likely that changes to soil physical properties will occur as a result of root growth of the cover crop. However, it is unlikely that good root growth is possible without good overall growth of the plant. Therefore, despite the roots being the part of the plant to directly affect the soil structure, the overall plant growth is also an important indicator of the soil physical properties (Vos et al., 1998, Greenwood et al., 1982) . Root growth has also been shown to be an important factor in catch-crop efficacy with root depth being well correlated with reduced nitrate content of the sub-soil (Thorup-Kristensen, 2001).

Cover crop species have been developed for their role due to the root morphology. For example, tap-rooted species such as tillage radish (*Raphanus* *sativus*), and white mustard (*Sinapis alba*), are known to have rapid root penetration rates that are effective at producing a dominant tap root with a large number of narrow lateral roots that quickly colonise the soil profile (Laine et al., 1993, Thorup-Kristensen, 2001). Cereal cover crops, on the other hand, do not produce a dominant taproot. Cereal roots tend to be laterally structured and less dense (Laine et al., 1993). In comparison to mustard, rye roots are more prolific in the shallow soil layers whereas brassicas have a relatively greater root length density in deeper soil layers (Bodner et al., 2010).

The effects of root growth on soil structure are not entirely as a result of total root length. In addition to root length, root diameter and production of root mucilage will also determine the effects on soil structure. For example, roots of varying diameters will produce a pore structure with varying diameters. It has been suggested that pores created by thick tap rooted species may have greater structural integrity than pores created by soil fauna such as earthworms (Whiteley, 1989, Blackwell et al., 1990) and root channels created by roots will produce pores that are better connected and contribute to increased hydraulic conductivity (Whalley et al., 2005).

It is these varied root characteristics between cover crop species that has led to the practice of combinations of species being used as cover crops for soil structural improvement. Combining a number of species with varying root behaviour may have a hybrid vigour effect compared with single species cover crops. This experiment aims to test the idea set out in sub-hypothesis two that combining species will have a positive effect on their growth and the soil structure. Cover crop seed is often sold commercially as pre-prepared mixes of species which are marketed as having benefits when grown in combination. In addition to multispecies combinations, dual species cover crops are also popular. A large motivation for including cover crops in the rotation is additional funding from the Rural Payments Agency. Farmers wanting to achieve the additional funding must have an established cover crop of at least two species between 1st October and 15th January (RPA, 2018). The combination of species must always have at least one cereal species and at least one non-cereal species.

It is well understood that with increased plant biodiversity, there will be benefits to greater overall biodiversity of soil flora and fauna (Bonkowski et al., 2009). It is unclear, however whether combining species in a cover crop will lead to a practical advantage over single species cover crops particularly as multi-species crops are considered more difficult to manage agronomically (Malezieux et al., 2009). It is often suggested that when growing species in combination, particularly for intercropping, the increase in plant biodiversity will have greater benefits than mono-culture cover crops (Hooper et al., 2005, Cardinale et al., 2011). However, the effectiveness of this has been disputed by (Finney et al., 2016). Where above ground biomass is concerned, crops that have vastly different canopy structures are likely to lead to competition. For example, a crop that is able to rapidly produce a tall canopy is likely to quickly outcompete a species that is slower to grow and produces a short canopy. If this were to happen, in cover crops, it is likely that the benefit of a combination will be mitigated. Nevertheless, traditional intercropping often makes use of contrasting crop growth for example, maize and oilseed rape have been the focus of intercropping with legume species in the UK and push-pull intercropping has been used for pest control in areas of Africa (Génard et al., 2017, Khan et al., 2010).

When considering combinations of species, effectiveness may also be reduced as a result of interactions between plants that may not be a result of competition between differing plant physiology. A number of studies have linked cover crop species such as rye (*Secale cereale*), hairy vetch (*Vicia villosa*) and red clover (*Trifolium pratense L.*) to the production of allelopathic chemicals that disrupt the growth of neighbouring plants reducing interspecific competition. Allelopathy may therefore be a limitation to growing in mixtures. This may have particular ramifications for cover crops grown as part of environmental focus areas as rye is one of the most popular cereal constituents of these cover crop mixtures (Dhima et al., 2006). Furthermore, it has been documented that the allelopathic chemicals released by hairy vetch are particularly effective at reducing the growth of white mustard, which is also a popular cover crop species (Ohno et al., 2000). As a result of these findings, it is unclear whether the theoretical benefits of combining cover crop species will translate into practical benefits in field conditions.

In Chapter Three, it was suggested that when rye and tillage radish plants were combined in a soil column, there was reduced root length density compared to treatments containing a species grown on its own. This trend was not seen for root biomass however that is likely to be as a result of the thickness of the tillage radish taproots. The diameter of radish taproots tended to exceed 4.5 mm and therefore could contribute greatly to root biomass over a very small length. With the inclusion of two or more species in cover crops becoming popular and occasionally necessary, it is important to understand the effect of combining two species when considering the overall growth of a cover crop and whether it would be beneficial to grow singular species cover crops.

4.2 Materials and methods

4.2.1 Experimental design

The experiment was set up in an unheated glasshouse on Sutton Bonington Campus on 8 March 2018. Popular cover crop species tillage radish (*Raphanus sativus*), white mustard (*Sinapis alba*), forage rye (*Secale cereale*) and black oat (*Avena strigosa*), were sown in pairs of plants in 2 litre pots of sandy loam soil. Each combination of the four species were combined into treatments (Table 4.1)

Table 4.1. Table of experimental treatments

Species 1	Species 2	Treatment name
White mustard	White mustard	MM
Tillage radish	Tillage radish	TT
Black oat	Black oat	OO
Forage rye	Forage rye	RR
White mustard	Tillage radish	MT
White mustard	Black oat	MO
White mustard	Forage rye	WR
Forage rye	Tillage radish	RT
Forage rye	Black oat	RO
Black oat	Tillage radish	OT

Treatments were replicated six times and were arranged into blocks containing a single pot of each treatment. As such the blocks were considered replicates.

Blocks were aligned across the glasshouse to account for variation in sunlight intensity. Pots were automatically irrigated to ensure that water availability was not a limiting factor in cover crop growth. The experiment ran for approximately 1200°C days assuming a base temperature of 0°C.

4.2.2 Cover crop growth

4.2.2.1 Above ground biomass

At termination of the experiment, above ground biomass samples were taken from each treatment. Leaf and stem material were removed from the plant at the soil surface. Each individual plant was sampled separately and therefore two samples were collected from each pot. Samples were then dried at 70°C until a constant mass was achieved which occurred after approximately four days. By separating each plant within a pot it was possible to get an indication of whether the growth of a species had been hindered by growing it in combination with another.

4.2.2.2 Root sampling

At termination of the experiment and when above ground samples had been taken, roots from the whole of each pot were washed and separated from soil using the Delta-T root washer (Delta-T, 1995). Clean root samples were then stored in fresh water at 3°C over-night prior to removal of organic matter.

Unlike above ground biomass, it was impossible to separate roots from each plant in a pot and therefore, a single root sample was taken from each pot.

Organic matter was separated from root material using a flotation technique using 2 mm, 50 µm and 20 µm sieves which allowed decaying organic matter to pass through the sieves leaving the root material to be collected, without damage, for image analysis.

4.2.2.3 Root scanning & analysis

Cleaned root samples were then spread across a Perspex tray and left to settle before being scanned using the WinRHIZO system. All samples were scanned within 48 hours. When images from each pot had been scanned, WinRHIZO software was used to measure root length, root diameter and root volume.

4.2.2.4 Root biomass

After scanning and analysis, root samples were collected and dried at 70°C until constant weight.

4.2.3 Statistical analysis

Statistical analysis was conducted on Genstat 19th Edition. General ANOVA was used for the majority of results in addition to generalised linear regression for regression analysis. Comparisons of statistical difference were made using the least significant difference that was calculated using the Fisher (1935) method on GenStat 19th Edition. LSD was only used when significant differences were found.

4.3 Results

4.3.1 Cover crop growth

4.3.1.1 Above ground biomass

No differences were seen between treatments MM, TT or MT which contained only brassica species. These treatments produced significantly more biomass than all other cover crop treatments (*P<0.01*) (Fig.4.1). Treatments OO, RR and RO produced significantly less biomass than all other treatments indicating that cereal cover crops produce the least above ground biomass. Treatments MO, MR, RT and OT produced an intermediate amount of above ground biomass. There appeared to be a trend for forage rye to produce more biomass than black oat however this was not statistically significant.

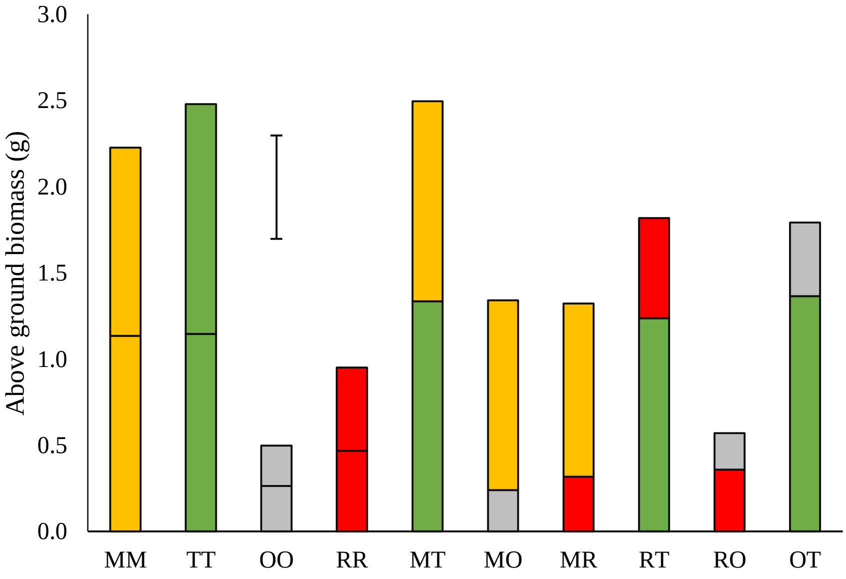


Figure 4.1 Mean above ground biomass of cover crop species. Bars represent total of both plants in each pot. Colours denote the species: yellow, green, grey and red being white mustard, tillage radish, and black oat and forage rye respectively. (*P<0.001*) error bar shows LSD 0.0968.

ANOVA analysis also revealed that no individual species, when separated for weighing, achieved a reduction or promotion of above ground biomass production when grown in combination with any other species (data not shown).

4.3.1.2. Root growth

Total root length density (Fig.4.2) was significantly greater for MM, TT and MT than OO, RR, MO, MR and RO (*P<0.001*) however, MM was not significantly higher than RT or OT. Treatments OO, RR, MR and RO had the lowest RLD however, there was no difference between MO and RT.

Figure 4.3 shows the RLD of roots within discreet diameter classes. MM, MT and TT produced significantly greater RLD up to 1mm diameter than all other treatments (Fig. 4.3a, *P<0.001*). RT, OT and MM had significantly higher RLD than OO, RR and RO but not MO and MR.

Between 1-2 mm diameters, MM had a higher RLD than all treatments except MT which was not significantly different to MM or any other treatments (Fig 4.3b). For roots with a diameter of 2-3 mm MM, TT, RR, MT, RT and OT produced a significantly larger RLD than OO however neither group was

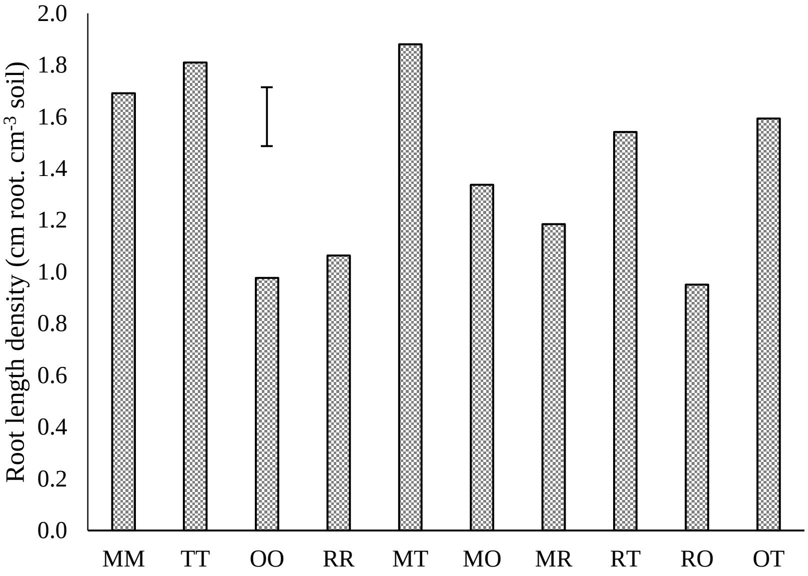


Figure 4.2 Mean total root length density of cover crop species. *P<0.001* Error bars showing LSD of 0.2292.

significantly different to MO, MR or RO (Fig.4.3c).

TT and MT had greater RLD between 3-4mm dimeter (Fig.4.3d, $P<0.001$) than all other treatments. RT and OT produced a significantly greater RLD than OO, RR, MO, and RO but there were no differences between the two groups and OT, RT, MM and MR.

CC, TT and MT produced the largest RLD of roots >4mm diameter which was significantly more than MO however there were no differences between RT and OT with MM, TT, MT or MO. OO, RR, MR and RO produced the smallest RLD which was significantly less than MO. MR however, was not significantly different to MO or the group: OO, RR, MR and RO.

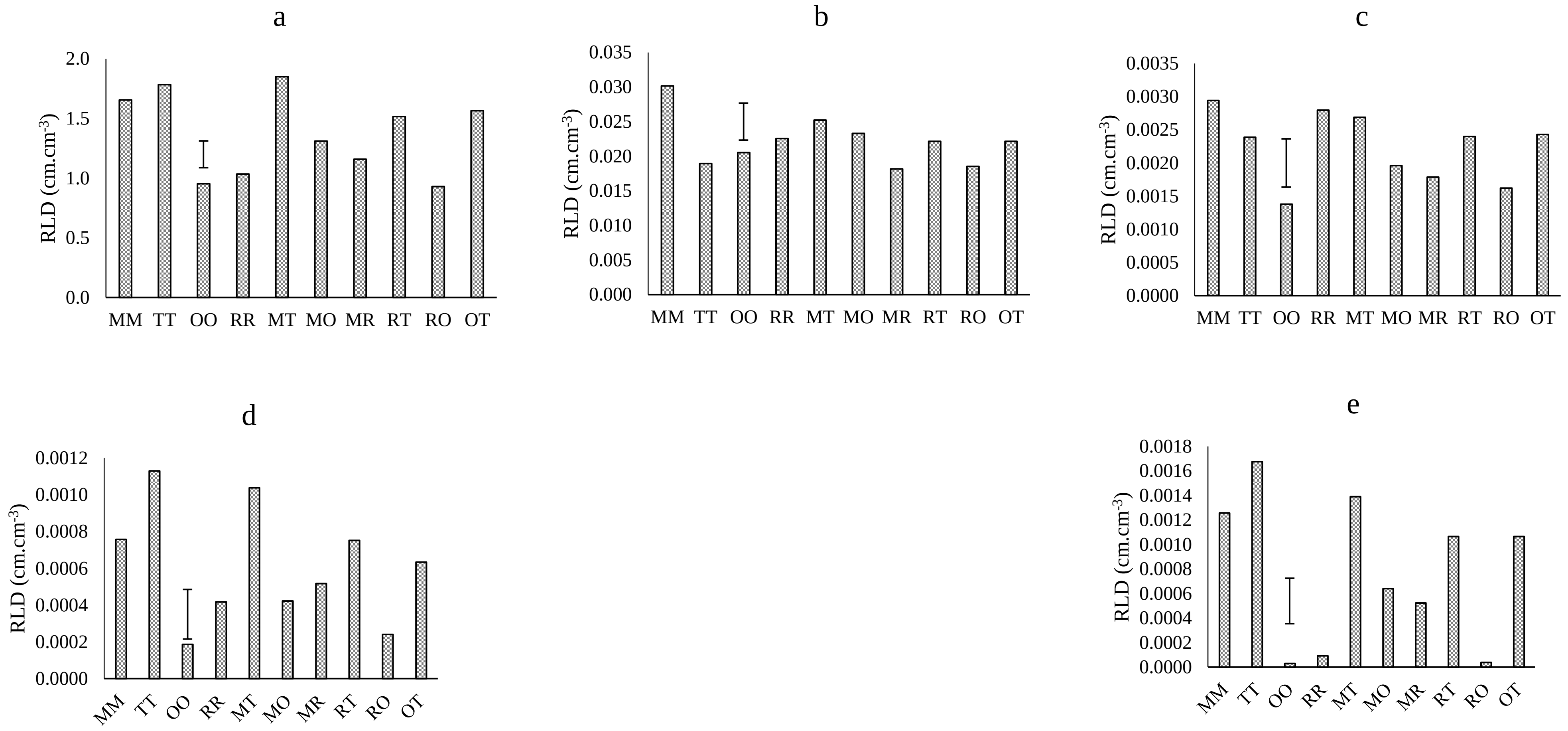


Figure 4.3 Root length density of cover crop treatments a) only including roots between 0-1 mm in diameter. P*<0.001* Error bars showing LSD 0.2242, b) Root length density of roots between 1-2 mm in diameter. *P=0.02* Error bars show LSD 0.0054. c) Root length density of roots 2-3 mm in diameter. *P<0.001*. Error bars show LSD 0.0007 d) Root length density of roots 3-4 mm diameter. *P<0.001*. Error bar is LSD of 0.0003. e) . Root length density of roots >4 mm diameter. *P<0.001*. Error bar showing LSD of 0.0004.

4.3.1.3 Relationship between above ground biomass and total root length density

A significant positive relationship was found between above ground biomass and total root length density which was maintained over species mixtures (*P<0.001*) showing that root growth was related to shoot growth.

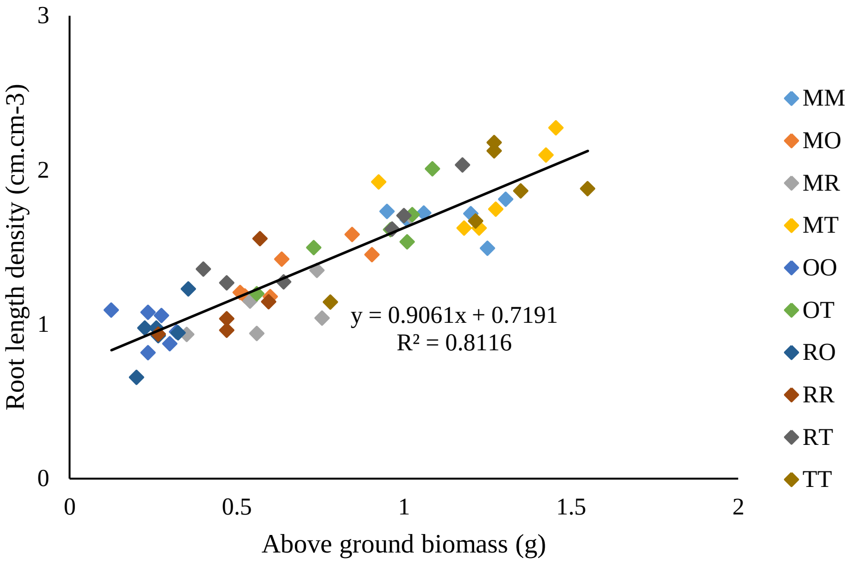


Figure 4.4 Regression of above ground biomass on total root length density. *P<0.001* d.f. 58

4.3.1.4 Shoot to root ratio

OO had a greater shoot to root ratio than MM, MO, MR, MT, OT and TT but not than RO, RR or RT. RO had significantly larger shoot:root than everything except RR & RT (Fig. 4.5, *P<0.001*).

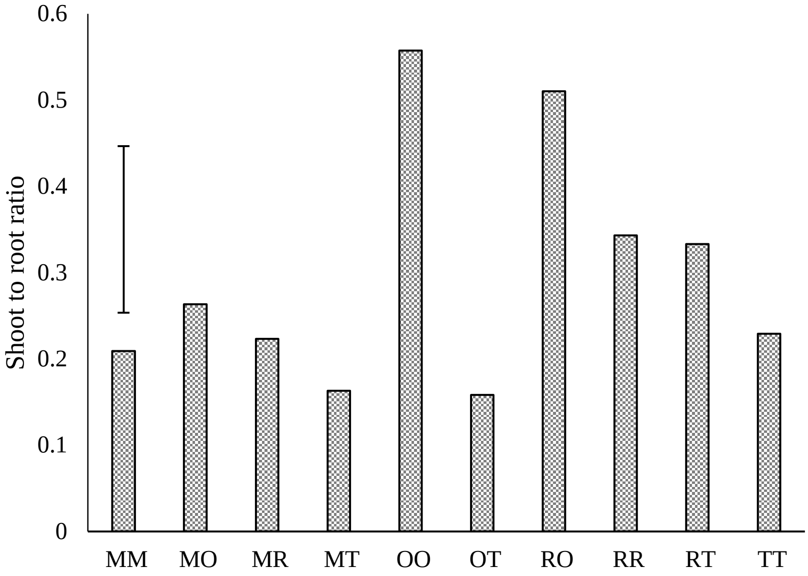


Figure 4.5 . Shoot to root ratio of treatments. *P<0.001* Error bars show LSD of 0.0958.

4.4 Discussion

4.4.1 Cover crop growth

Treatments containing brassicas produced the most biomass. Combining brassicas and cereals produced an intermediate quantity of biomass. The specific species did not appear to have an influence on biomass production. This is shown by the lack of positive or negative effects of combining species on above ground biomass production.

Recent experiments in Germany have also shown that in the first 12 weeks after planting there were no differences in above ground biomass between mustard or forage radish (Brust et al., 2014). Allison et al. (1998a) found that when cover crops are sown in mid-summer, biomass production is greater in radish than mustard whereas when cover crops were sown in early autumn mustard produced significantly more biomass than radish. It was concluded that the limitation to brassica cover crop growth is a result of access to soil moisture. Smaller seeds are more likely to be affected by poor water availability. As mustard seeds are smaller than radish seeds they are more vulnerable to water scarcity at drilling (Allison et al., 1998a). The lack of differences in biomass production between radish and mustard in this experiment are therefore likely to be attributed to the lack of water stress experienced by the plants and the growth period not being so long that mustard reached the size it would in field conditions where mustard is more than likely to produce greater amounts of biomass than radish.

4.4.2 The effect of combining cover crop species on growth

It is possible that when species are grown in the field, shading from other plants may result in different shoot biomass production. Field studies have suggested that competition between species may reduce growth of one plant or may have triggered elongation of shoots to compensate for lack of incident radiation (Craine and Dybzinski, 2013).

4.4.3 Cover crop root growth

Following the same trend as above ground biomass, treatments containing brassicas produced the greatest root length density while those containing only cereal cover crops produced the lowest root length density. It is possible that this is as a result of cereal root growth being more extensive compared to dense rooting of the tap rooted brassicas. When cereal cover crops were combined with tillage radish they produced significantly greater RLD of roots above 4.5 mm diameter than when both cereals were combined with mustard. This may suggest that although no overall benefit has been seen of combining the species, there does appear to be a benefit of combining cereal cover crops with tillage radish over mustard as greater root diameter may produce more stable soil pores (Blackwell et al., 1990). When brassicas were combined there was no difference in root growth. This suggests when a cereal was combined with a brassica there was an overall reduction of root growth. Brust et al. (2014) found that, after 12 weeks of growth, radish produced significantly more root biomass than white mustard. It is possible that in the field this was sufficient time for radish taproots to swell in comparison to the mustard producing differences in root biomass.

The majority of total root length density can be explained by fine roots. This reflects the root elongation rate of brassicas being more rapid than that of cereal species (Thorup-Kristensen, 2001). When mustard plants were combined they produced significantly more roots than all treatments except when mustard was combined with radish. This is likely to be a reflection of brassica root architecture which produces thick secondary roots from the taproot which tend to be thicker than cereal lateral roots in this experiment. Furthermore, the secondary roots from radish tend to be of a smaller diameter than mustard secondary roots. This shows brassicas produce both more root length overall and also have more variable root diameters than cereal cover crops. Cereal and brassica species are often combined to get the supposed benefits of a thick tap root from a brassica and the lateral roots of a cereal which in theory should produce a number of biopores through the soil with varying diameters (Blackwell et al., 1990, Han et al., 2015). In the current experiment, the brassica treatments produced the most diverse range of roots which are likely to have produced the most diverse range of biopores (Blackwell et al., 1990). This suggests that there is little point in combining cereal and brassica species in order to make use of their different rooting structures.

4.4.4 Relationship between aboveground and belowground growth

In this experiment we found a strong relationship between above ground biomass and root length density. However, looking at the shoot:root shows that there are significant differences between the partitioning of biomass between each treatment. Oat and rye & oat had a significantly greater shoot to root ratio. This suggests that when oat was in combination with itself and rye it produced more root biomass per unit of above ground biomass. This further suggests that when oat is combined with other species there is a negative impact of partitioning biomass to the roots. It is possible that this effect is not seen when rye and oat were combined due to the similarities of growth between the two species.

4.4.5 Implications of these findings on Farmers

It is likely that farmers aim to maximise the effects of cover crops on soil structure while minimising above ground biomass. Excess crop residues can be of detriment to the establishment of the following crop (Morris et al., 2009) as the soil surface may be prevented from drying in the spring therefore excess biomass can indirectly result in poor sugar beet establishment. Seedbed preparation for sugar beet can be affected by soil surface moisture. If the soil surface moisture is too high it can be difficult to produce a seedbed that allows for good seed to soil contact and germination of the sugar beet seed (Blunk et al., 2018, Atkinson et al., 2007, Durr and Aubertot, 2000) . If a cover crop that partitions more biomass to root growth than shoot growth then excess soil moisture could be avoided. Nevertheless, if the primary objective is to produce the greatest root biomass and length irrespective of above ground biomass it is likely that a brassica cover crop would be most effective. In long term experiments, the leaf turnover of brassica cover crops is related to an increased earthworm population (Crotty, 2018). With an increase in worm population there is likely to be an increase in the rate of biomass decomposition which may, in the long term, reduce the risk of the soil surface moisture being too great to produce an optimum seedbed.

4.5 Conclusions

Black oat produced more root biomass per unit of shoot biomass, showing that it may be more optimal for cover crop users who want to maximise root growth while reducing the risk of excess crop residue when establishing the following crop.

Overall brassica cover crop species produced significantly more root length than cereal cover crops and there were no differences within those two groups.

Brassica cover crops also had a larger range of root diameters which may mean that a dense brassica cover crop is more effective at producing biopores with varying sizes compared to cover crop combinations.

There did not appear to be any positive or negative effects of combining two species. When brassica and cereal species were combined the overall effect was to produce an intermediate root length density showing that there were no adverse effects of combining the two species.

Overall we are not able to accept the idea that combining cover crop species will always result in greater root growth and thus a greater influence on the soil structure as suggested in sub-hypothesis two. What may be the case is enhanced cover crop growth where a legume cover crop is combined with a non-legume in nutrient limiting conditions. However, this was not investigated in this experiment.

Chapter 5: The effects of cover crops on soil structure and sugar beet growth and yield

5.1 Introduction

Chapter two focused on the effects of cover crop roots on soil aggregation. This relationship was further explored in Chapter three when looking at the effects of cover crops on soil structure and growth of sugar beet in controlled conditions. These two experiments did not, however, contribute to understanding the growth and effects of cover crops in the field, where temperature and rainfall in particular, are highly variable between seasons. Thus, this experiment aims to understand the ideas set out in sub-hypotheses 1a, b, c, d, & f where we aim to understand the effects of root characteristics, air temperature, rainfall, crop water use and soil volume on the soil structure during and following a cover crop.

The choice of autumn sown cover crops is largely based on the ability of species to establish a large canopy and root structure in the cool conditions of temperate autumn, in contrast to cash crop species, which are usually chosen for the usability of their seeds or storage organs. Typical cover crops tend to be rapid growing brassicas, cereals and legumes for example oil radish (*Raphanus sativus*), black oat (*Avena strigosa*) and Egyptian clover (*Trifolium alexandrium*).

Past research has mostly focussed on the ability of cover crops to reduce nitrate leaching during the autumn (Cooper et al., 2017, Allison et al., 1998a) . There is, however, little UK research on their impacts on soil structure, and even less that goes on to explore their effect on cash crop yield. In addition, it is also uncertain whether the nitrates absorbed during the autumn will have a positive impact on crop growth in the following spring.

From a legislative point of view, it is possible to establish a cash crop following a cover crop in the autumn. However, it is more likely that growers, particularly on heavy textured soil, will aim to establish a spring crop following a cover or catch crop. Typical UK spring crops include spring wheat, spring barley, spring field beans, maize, field peas and sugar beet which all tend to be established between February and May. Spring sown crops suit this drilling timing primarily as they do not require a cool vernalisation period to produce fruiting bodies for harvest. Farmers make the decision to sow spring crops partly due to them allowing a greater window of opportunity for weed control during the autumn months and also for their niche market use such a spring malting barley. The opportunity to use spring cropping as a way to also establish a cover crop between the harvest of the previous crop and the establishment of the spring crop is quickly becoming a popular management practice in the UK.

The UK sugar beet crop is grown on a wide range of soil types which have tillage practices and crop rotations that are specific to each farm. It has been suggested that the primary limitations to brassica cover crop growth is soil moisture in the early autumn whereas the primary limitation to cereals is the air temperature (Allison et al., 1998a).

Cereal cover crops have been linked to the production of root mucilage which may provide the binding properties that may influence active soil aggregation (Monroe and Kladivko, 1987, Mench et al., 1987). Furthermore, differences in freeze-thaw cycles have been shown to interact with cover crop roots to alter the aggregation of soil (Wang et al., 2012). Similarly, the influence that plant roots have on the aggregation of the soil has been closely linked to organic matter and clay content.

In addition to the root growth of the cover crop, the above ground, or leaf biomass, is also critical to the effects that cover crops have on the soil profile. The production of leaf biomass has been linked to increases in earthworm populations (van Groenigen et al., 2014). It has been suggested that short term cover crops that are sown in the autumn are able to positively influence the population of earthworms by providing a food source that would not normally be present in the winter months (Korucu et al., 2018). It has also been suggested that earthworm populations contribute to the production of soil channels which contribute to the aeration of the soil profile and may also provide channels that allow easier root growth to subsequent plants. However, recent studies have suggested that the short period of cover crop growth is not sufficient time to contribute as a food source for *Lubricious* deep burrowing earthworms that are able to contribute the most to soil aeration (Stroud et al., 2017).

It is possible that the cover crop canopy will also contribute to the depletion of soil moisture in the soil profile (Allison et al., 1998a). It has been suggested by Allison et al. (1998a) that this may have detrimental effects on water availability to the following sugar beet crop and to the restoration of ground water during the winter. However, the drying of the soil may allow earlier cultivation of a seedbed the following spring which may lengthen the sugar beet growing season and therefore increase yield potential.

In order to maximise this potential there may have to be trade-offs with reduction in soil moisture by allowing cover crop growth and a sufficient period of time to allow decomposition or removal of leaf biomass which may trap water in the soil profile potentially hindering the production of the sugar beet seedbed. It is unclear whether there are differences in the severity of this effect depending on the species of cover crop and we aim to use techniques such as electromagnetic conductivity to understand the effects of cover crop growth on soil moisture and the subsequent effects on the growth of sugar beet in relation to water availability. This technique has been able to detect differences in water uptake between different winter wheat cultivars and therefore may offer a non-destructive measurement of soil moisture and structure that can be used over time to understand the effects of cover crops on growth of the subsequent sugar beet crop (Shanahan et al., 2015). This also offers to opportunity to investigate sub-hypothesis three which is to understand how cover crops may influence water and nutrient uptake by the subsequent sugar beet crop.

5.2 Materials & methods

5.2.1 Experimental design

The field experiments were conducted over two field seasons at Sutton Bonington Campus, University of Nottingham. Experiments started with establishment of cover crops on 1 September 2016 and 2 September 2017. In both years the experiment was conducted on a sandy loam soil that was part of the Dunnington Heath soil series. The topsoil has the following constituents 66% sand, 18% silt, 15.6% clay. The experimental area was prepared by minimum-tillage cultivation to remove soil constraints from the previous crop and was established using a combination drill. Cover crop treatments (Table 5.1) were arranged in a randomised block design with four blocks across the soil variation. Single replicates of each treatment were randomly placed within a block. As a result there were four replicates of each treatment in the experiment. Plots were 3m x 12 m in 2016. Plots were doubled in size in the 2017-2018 field season to allow for a destructive and non-destructive area to facilitate collection of soil measurements without damaging the soil profile for sugar beet growth analysis. Cover crops were grown until the first week of December in both 2016 and 2017 before being mown across the blocks to kill all treatments. This date was chosen to allow a sufficient period of time for leaf biomass to decompose before sugar beet drilling. In February of 2017 and 2018 the area was sprayed with glyphosate to ensure cover crop plants would be killed.

Table 5.1. Cover crop treatments for 2016 & 2017

Common name	Variety	Latin name	Seed rate kg ha^{-1}
Oil radish (2016/17 only)		*Raphanus sativus*	30
Tillage Radish	Mino	*Raphanus sativus*	15
Tillage Radish	Mino	*Raphanus sativus*	30
Forage Rye	Protector	*Secale cereale*	55
Black Strigosa Oat	Pratex	*Avena strigosa*	35
White Mustard	Rota	*Sinapis alba*	10
Egyptian Clover	Tim	*Trifolium alexandria*	10
Vetch	Buza	*Vicia spp*	35
Forage Rye & Tillage Radish (2017/18 only)	Protector & Mino	*S. cereale & R. sativus*	25 7
Bare Soil			
Bare Soil Ploughed (2017/18 only)			

Sugar beet seedbeds were prepared on each plot using a disc cultivator set to 10 cm depth. The sugar beet variety KWS Sabatina was used for the whole experiment and this was drilled at a rate of 1.2 units ha^{-1} which is the equivalent of 120,000 seeds ha^{-1}. In 2017 the experiment was drilled with sugar beet on 7 April, in 2018 drilling took place on 11 May as a result of the late cold snap in spring 2018.

5.2.2 Measurements during cover crop growth

5.2.2.1 Penetration resistance

Penetration resistance was measured regularly during the growth of the cover crop and early growth of the sugar beet. Five cone insertions were made per plot at each time point using the Rimik CP40II penetrometer that logged penetration resistance every cm to 70 cm depth. The five insertions were then averaged to give a single penetration resistance for each depth through the soil profile. In the cover crop growing season of the second year of experiments, the penetrometer was broken and so the data set is incomplete.

5.2.2.2 Bulk density and soil moisture content

Bulk density was taken regularly from the soil surface during both experimental seasons. A standard sized sample was taken using a bulk density ring with a volume of 140 cm^3. Samples were weighed fresh, dried at 105^{o}C until constant weight was achieved and then weighed immediately after. The difference between soil fresh weight and dry weight allowed calculation of soil moisture and bulk density in g.cm^{-3}. Bulk density measurements were taken during cover crop growth on 10 December 2016 in the first year, and 8 October 2017 & 16 January 2018 in the second year. Samples were also taken from and from the sugar beet seedbed on the 10 April 2017 in the first year and the 17 May 2018 in the second year.

5.2.2.3 Aggregate size distribution

Bulk samples of each plot were taken to a depth of 20 cm at several points during the season. Samples were taken at cover crop destruction and at sugar beet drilling at the same dates as bulk density samples. Samples were spread out and allowed to air dry for at least 4 days. Dried samples were passed through a cascade of sieves with diameters of 10 mm, 6 mm, 5 mm, 4 mm, 3 mm, 2 mm, 1 mm 500 µm, 50 µm & 20 µm. Samples left on each sieve were weighed and a distribution of the aggregates were recorded.

5.2.2.4 Shear strength

Shear strength of the soil surface was taken at the same time points as aggregate size distribution to assess the lateral shear strength of the soil surface. Measurements were taken using the Edeco Pilcon Hand Vane of the top 5 cm of the seedbed.

5.2.2.5 Assessments during cover crop growth

At the end of each cover crop growing period measurements of above ground biomass were taken. From each plot leaf material was collected from 3 m^2 of the plot, which was taken from the centre of each plot, and dried at 70^oC until a constant weight was achieved.

In the second year of field experimentation, three assessments of cover crop rooting were taken between October and December. A soil corer with a diameter of 5 cm and a depth of 20 cm was inserted into the destructive plots 10 times. Samples were bulked and roots washed using the Delta-T root washer to remove soil and organic matter. Clean samples were scanned and analysed using the WinRHIZO system to get root length and root diameter.

5.2.2.6 Earthworm counts

In the second year of field experiments, in the destructive areas of plots, counts of total earthworm populations were made monthly during the cover crop growing season. Earthworm species were not determined and weight was not measured.

5.2.3 Measurements during sugar beet growth

5.2.3.1 Soil nitrogen

One week prior to sugar beet drilling in both field seasons, soil mineral nitrogen samples were taken from each plot to a depth of 90 cm. The top 30 cm was bulked together as one sample and soil from 30-90 cm depth was analysed as a separate sample. Samples were immediately analysed by NRM Ltd for soil mineral nitrogen content and available nitrogen content.

5.2.3.2 Establishment & canopy cover images

From drilling date, weekly canopy images were taken using the method described in Wright et al. (2018). A Canon 1100D was mounted on a frame that allowed images to be taken directly above the plots. A wide angle 10-18 mm lens was fixed at 10 mm and held above the plot at a height of 1.2 m and 2.5 metres from the edge of the plot. The centre three rows of sugar beet were aligned within the view of the lens. One photo was taken from each end of the plot capturing a total of 72% of the area of each plot. Establishment counts were taken when plants reached four mature leaves. Canopy green area was measured by thresholding each image on ImageJ for green area (Rasband, 2011).

In addition to canopy images, a Holland Scientific Crop Circle was mounted on the same frame to measure the NDVI and NDRE of each plot. The device was mounted at the same height, adjacent to the camera in order to measure the same area of each plot.

5.2.3.3 Measurements of sugar beet growth

Harvest of the experiment took place in the first week of 30 September 2017 and 31st October 2018. Yield samples were harvested by the British Beet Research Organisation Trials Team. From each plot, the central three rows were lifted and processed through the British Sugar Tare house. Samples were weighed fresh and washed to indicate plot weight, samples of sugar content were also taken from these samples. In addition, 10 sugar beet were lifted by hand and weighed for fresh weight. These were then subsampled to five which were dried at 70°C for approximately one month when a constant weight was achieved and crop biomass was recorded.

After harvest of the plots row five was lifted by hand and then scored for fanging as shown by Figure 5.1.

Figure 5.1 Root morphology of sugar beet. Left: Beet considered not fanged Right: Beet considered to be fanged

5.2.3.4 Soil ERT and EMI

Soil electrical resistance tomography (ERT) and electromagnetic induction (EMI) have been used to characterise the influence of roots in the rooting zone of the soil profile. ERT and EMI were measured at several points in the experimental seasons. In the first year (2016-2017) measurements were taken in October, November and December during cover crop growth and March, May and June during sugar beet growth. Measurements were taken in October, November and December during cover crop growth in the second year (2017-2018) and March, May, June, August and October during sugar beet growth.

ERT measurements involved inserting electrical probes into the soil profile at 15 cm intervals to a depth of approximately 10 cm. ERT probes were arranged in a line along the middle of a discard plot and the same plot was used at each date. A Syscal Pro electrical resistivity meter (Iris Instruments, Orleans, France) was used to measure apparent electrical resistivity. These data were inverted to give a 2D distribution of soil resistivity. Data was then converted into conductivity to give an electrical conductivity profile which was used to calibrate EMI data.

The EMI data was collected without the need of inserting probes into the soil profile. The apparent electrical conductivity gives a number of measurements that corresponds with the distance between transmitter and receiver coils in the probe and their direction. A CMD mini-explorer (GF instruments, Czech Republic) device was used as in Shanahan et al. (2015), to take measurements of the apparent soil conductivity (σ_a) at three positions along the centre of the plots. The instrument has a 30-kHz transmitter coil and three receiver coils at different spacing from the transmitter. The coils can be orientated vertically or horizontally by rotating the probe by 90^o on the long axis. The different coil depths allowed measurements of EMI to be taken at six points through the soil profile. These depths were 0.25 m, 0.5 m, 1 m from the vertical planar and 0.49 m, 0.8 m, 1.8 m from the horizontal planar. A drift base was chosen at a set point between blocks two and three which would allow for the probe to be taken back to between measurements of each block for calibration against ambient temperature.

5.2.4 Statistical analysis

Statistical analysis was conducted on Genstat 19th Edition. One way ANOVA analysis was used to analyse the data. Blocking was taken account of within the analysis which was used to account for variation across the field area. Significant differences between means were compared using LSD as the displayed error bars. LSD was calculated using the Fisher (1935) method and used as the comparison between means of each treatment.

5.3 Results

5.3.1 Weather data

Rainfall for the period of cover crop growth was different for both years. In both seasons rainfall was relatively even throughout the autumn with more occurring towards the winter months however in 2016 total rainfall during cover crop growth was approximately 150 mm whereas 2017 received approximately 250 mm rain (Fig.5.2a). Accumulated thermal time was very similar between the two years (Fig.5.2b). Early September was warmer in 2016 than 2017.

During the 2017 sugar beet growing season the crop received a total of 450 mm rain. This occurred at regular intervals during the growing season (Fig.5.2c). In spring/summer 2018 rainfall was much lower with 0 mm rainfall between one and ten weeks after sowing and there being a total rainfall of just 175 mm throughout the growing season (March-October).

In 2017 sugar beet received a total of 2500^{o}C days of thermal time compared with a total of 2000^{o}C days in 2018. However, air temperatures were much higher in 2018 and thermal time would have exceeded 2017 if the same drilling date had occurred. The high temperatures of summer 2018 resulted in thermal time being accumulated at a much faster rate (Fig.5.2d).

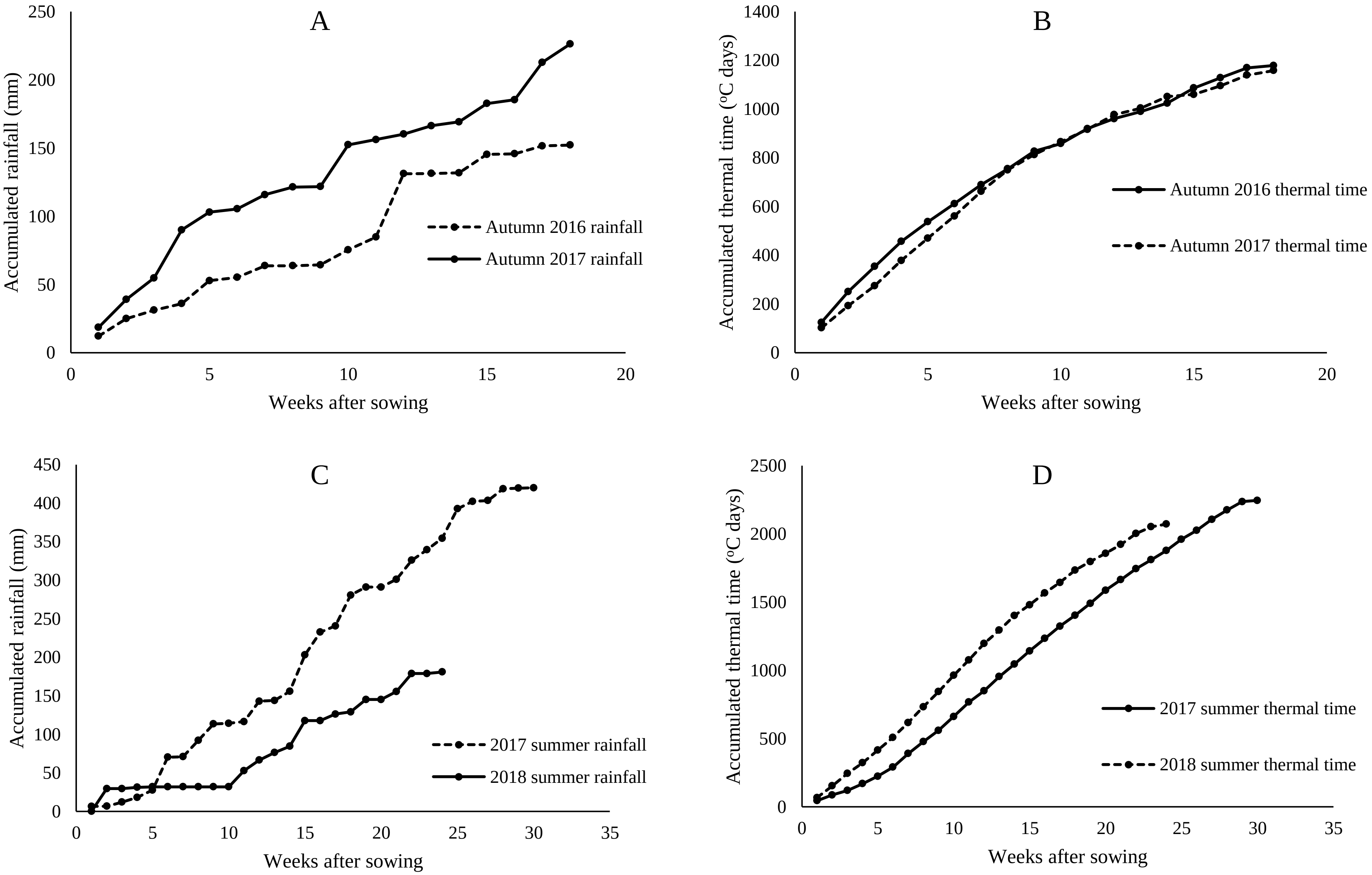


Figure 5.2 A) Accumulated rainfall from point of cover crop sowing in each autumn. B) Accumulated thermal time through the autumn from drilling of cover crops using $0^{o}C$ as base temperature. C) Accumulated rainfall after sugar beet drilling in spring. D) Accumulated thermal time from sugar beet drilling above base temperature of $3^{o}C$.

5.3.2 Soil conditions

5.3.2.1 Soil moisture

Over time, in both experimental years, soil moisture increased from autumn to winter. In March 2017, soil moisture was greater than in autumn 2016 however, in 2018, soil moisture was significantly lower than the previous winter measurement (Fig.5.3). In 2017, mustard resulted in the lowest soil moisture content in October, tillage radish was second driest and significantly drier than all treatments except mustard. In November and March 2016/2017 there were no differences between oil radish and white mustard. In March 2016/2017 white mustard, oil radish, tillage radish and Egyptian clover all had significantly lower soil moisture than forage rye, black oat and vetch.

Overall, 2017/2018 soil was drier than the previous year in all treatments and throughout the first stage of the experiment ($P<0.001$ Fig.5.4). In October, ploughed soil resulted in lower soil moisture than all other treatments. In January there were no differences between ploughed soil, bare soil or tillage radish sown at 15kg ha^{-1} however these had lower soil moisture than the remaining treatments. At sugar beet drilling in May, the differences in soil moisture were very small. Ploughed soil, white mustard and tillage radish & forage rye resulted in lower soil moisture than black oat, bare soil, Egyptian clover, vetch and tillage radish 30kg however there were no differences between these treatments and tillage radish 15kg and forage radish.

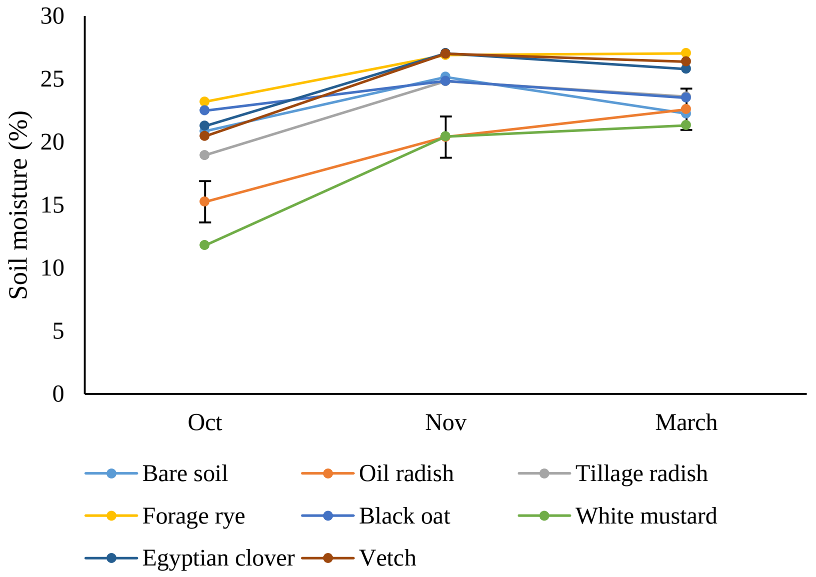


Figure 5.3 Soil surface moisture over time in 2016/17. Differences present between treatment and sample date. Differences between treatments *P<0.001*. Differences between dates *P<0.001*. Error bars = LSD 1.948.

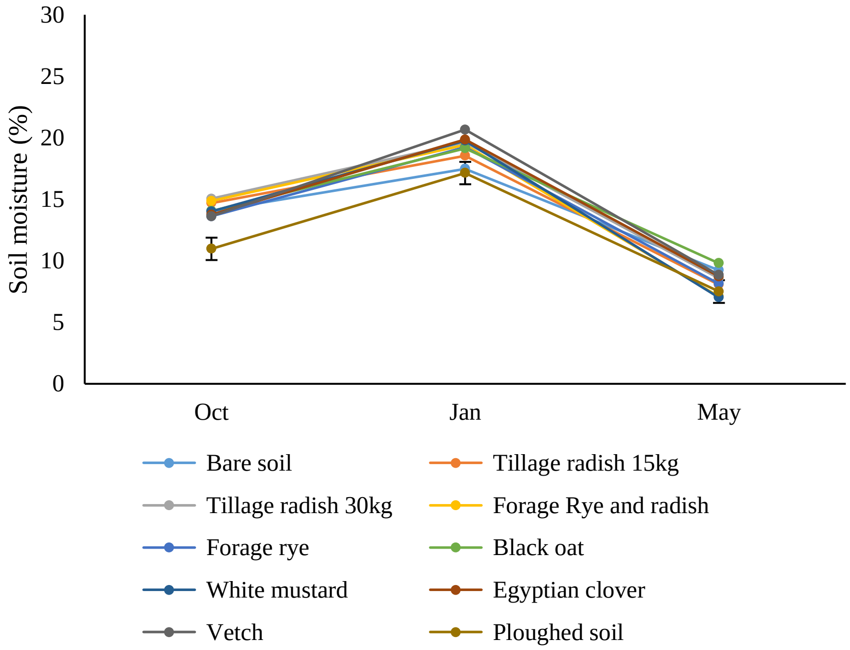


Figure 5.4 Soil surface moisture over time in 2017/18. Differences between treatments, sample date and an interaction between sample date and treatment. *P<0.001*, *P<0.001*, *P=0.05* respectively. Error bars show combined treatment and sample date LSD 1.816

5.3.2.2 Bulk density

There were no differences in bulk density between treatments at any sample date in either experimental year. There was an increase in bulk density between the end of cover crop growth and sugar beet drilling in the first year whereas bulk density increased during the winter of the second season but seedbed bulk density was lower than the January measurement. In both years the average bulk density at sugar beet drilling was 1.2 $g.cm^{-3}$ (Fig. 5.5 & 5.6).

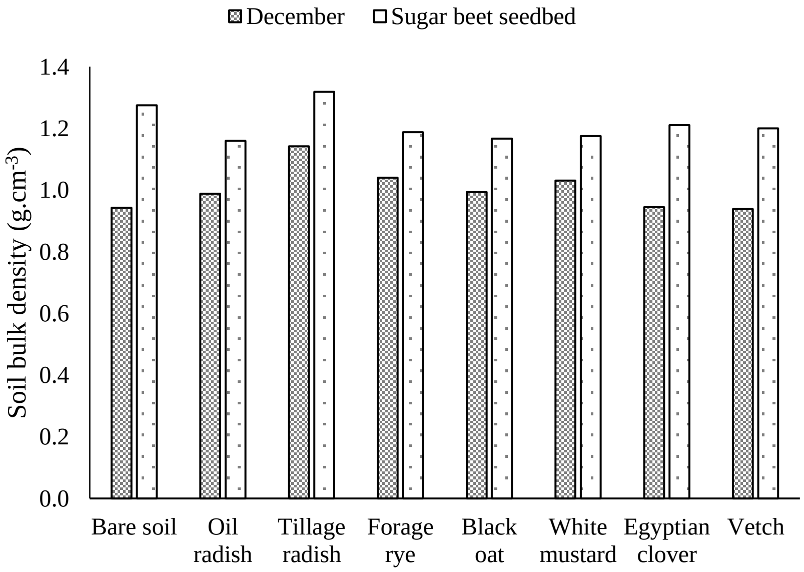


Figure 5.3 Mean bulk density of the soil surface in December 2016 and March 2017 immediately prior to sugar beet drilling. No differences between treatments at either depth.

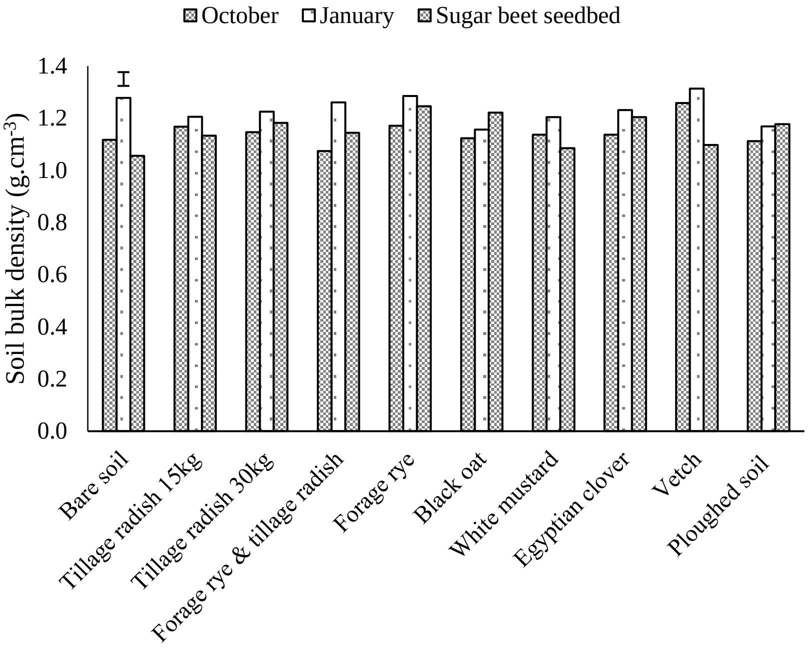


Figure 5.4 Mean bulk density in October 2017, January 2018 and May 2018 at sugar beet drilling. No differences between treatments at any date however, significant differences between dates *P<0.001* Error bars show LSD 0.163

5.3.2.3 Shear strength

No differences in shear strength were recorded in the first experimental year and shear strength remained at an average of 8.6 kPa (Fig.5.7). In the second experimental year ploughed soil had consistently lower shear strength than all other treatments (*P<0.001*). In addition, shear strength in May was

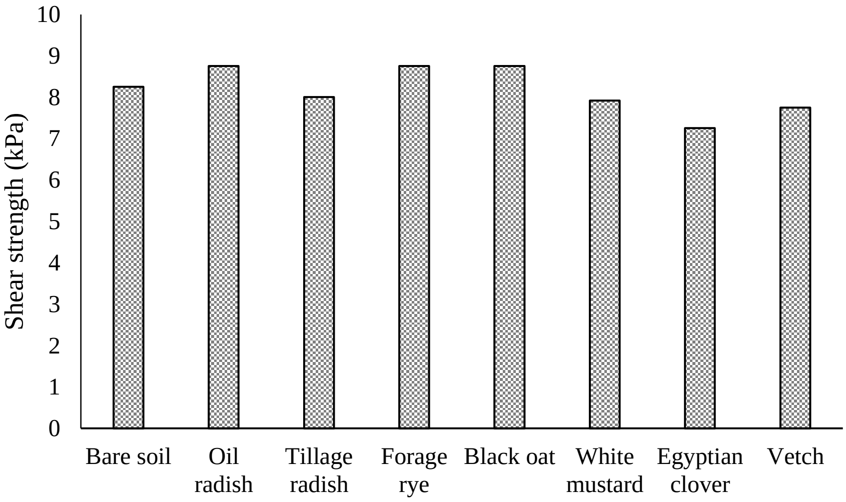


Figure 5.7 Shear strength of first experimental year samples at point of cover crop destruction. No differences between treatments.

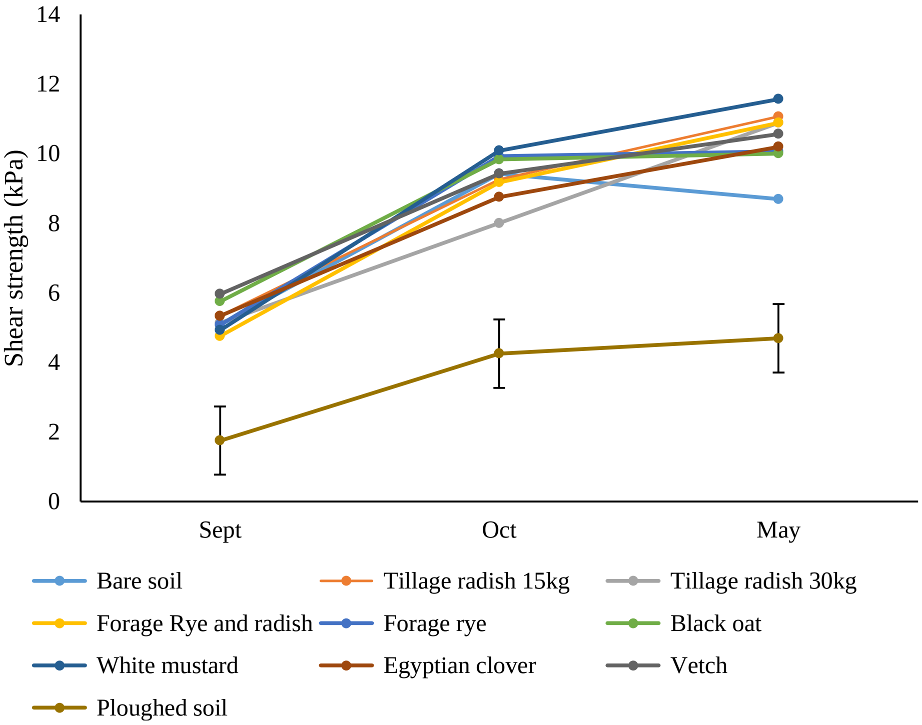


Figure 5.8 Shear strength of second experimental year. Significant differences between treatment *P<0.001* and between sample date *P<0.001*. Error bars show LSD 2.071.

significantly greater than in October for all treatments (*P<0.001*) (Fig.5.8).

5.3.2.4 Soil aggregation

There were no differences in soil aggregate size distribution as a result of the cover crop treatments at any measured point during cover crop growth over the two experimental years (Figures. 5.9, 5.10, 5.11). Aggregate mean weight diameter was greater during cover crop growth than in the sugar beet seedbed in the first season (Fig.5.11). No treatment resulted in a significantly different mean weight dimeter of aggregates than any other treatments. There were no differences in MWD in the second year of cover crop growth between treatments but MWD was greater in cover crop growth than in the sugar beet seedbed (Fig.5.12).

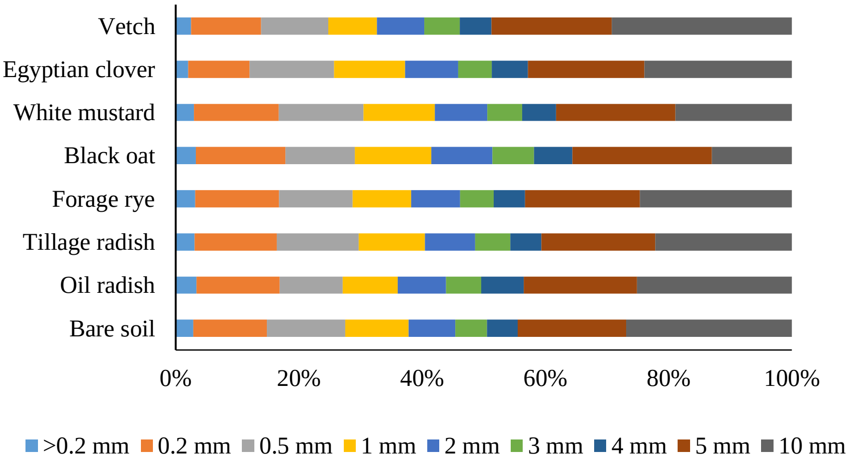


Figure 5.5 Aggregate size distribution of first experimental year measure immediately after sugar beet drilling. No significant differences.

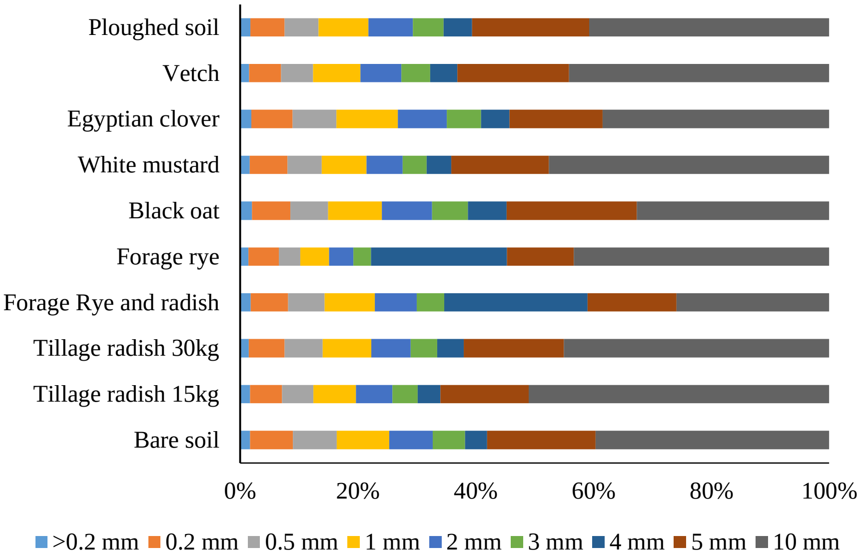


Figure 5.6 Aggregate size distribution of second experimental year measured immediately before cover crop destruction.

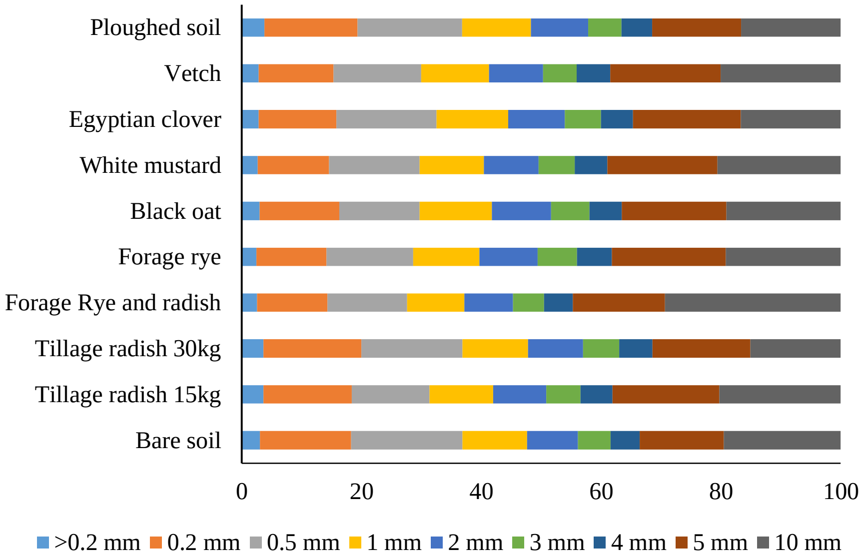


Figure 5.7 Aggregate size distribution of second experimental year immediately after sugar beet drilling.

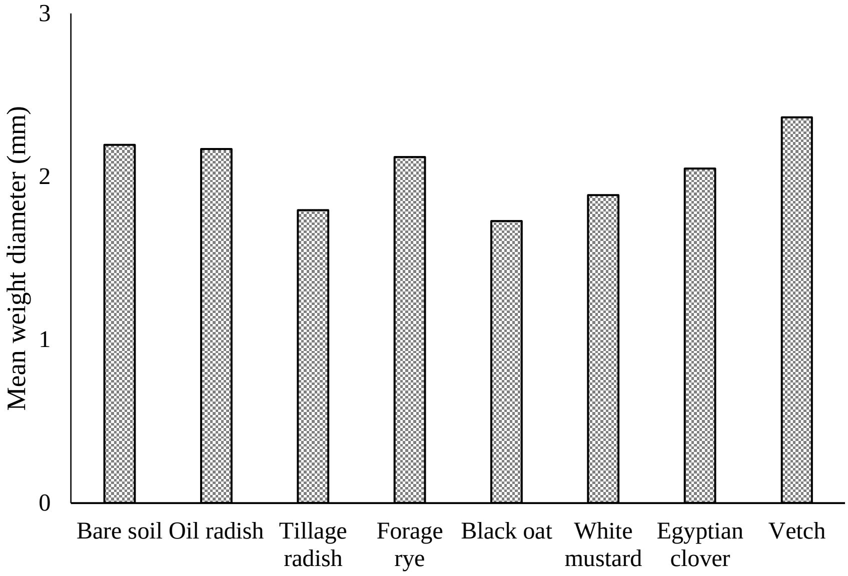


Figure 5.8 Mean weight diameter of first experimental year sugar beet seedbed aggregate size distribution. No differences between treatments.

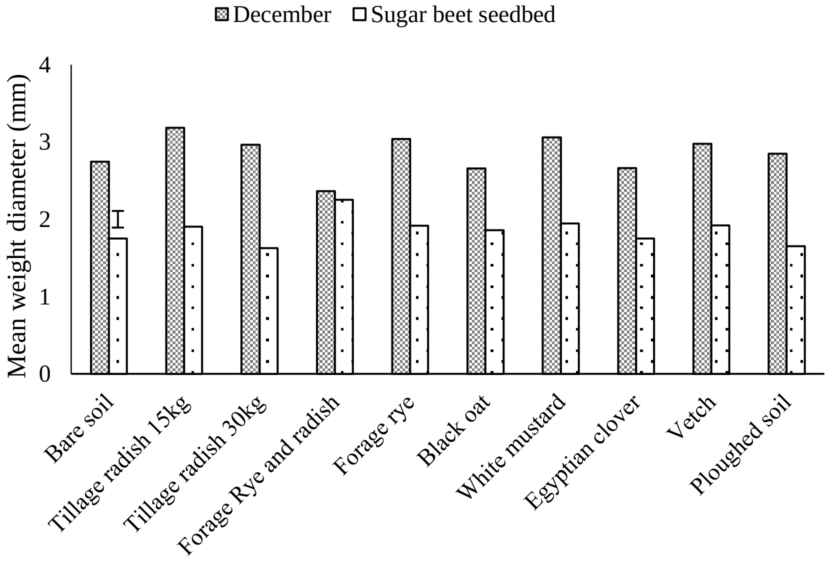


Figure 5.9 Mean weight diameter from second experimental year showing both sample points, at cover crop destruction and at sugar beet drilling. No significant differences between treatments at either date. Significant differences between two dates *P<0.001*. Error bars show LSD 0.2148

5.3.2.5 Penetration resistance

Penetration resistance during the first experiment did not vary between treatments at either date measured (Fig. 5.15 & 5.16). In March 2017, all treatments resulted in relatively low penetration resistance in the top 40 cm where penetration resistance remained below 2 MPa. At drilling in 2017 penetration resistance for all treatments had increased by approximately 0.5 MPa at all depths.

In the second year of experimentation, the penetration resistance of the soil profile was significantly lower after ploughed soil than all other treatments in March ($P<0.001$ Fig.5.16). At sugar beet drilling, differences between treatments had disappeared (Fig.5.17). In comparison between the two dates there were no large increases in overall penetration resistance however within the top 15 cm of soil, the penetration resistance had increased by 0.5 MPa while below 15cm there was no increase in penetration resistance.

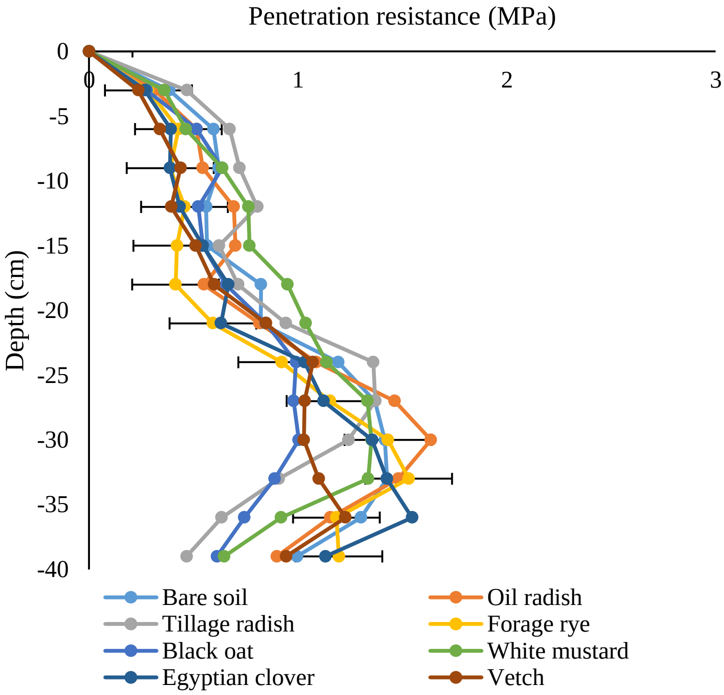


Figure 5.14 Soil penetration resistance of first field experiment one month before sugar beet drilling on the 8th March 2017

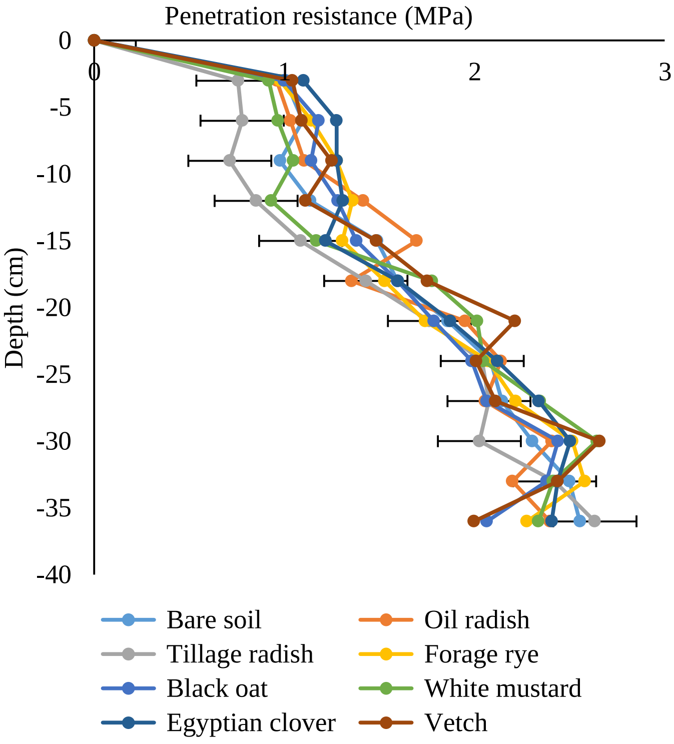


Figure 5.15 Soil penetration resistance of first field experiment immediately after sugar beet drilling on the 10th April 2017.

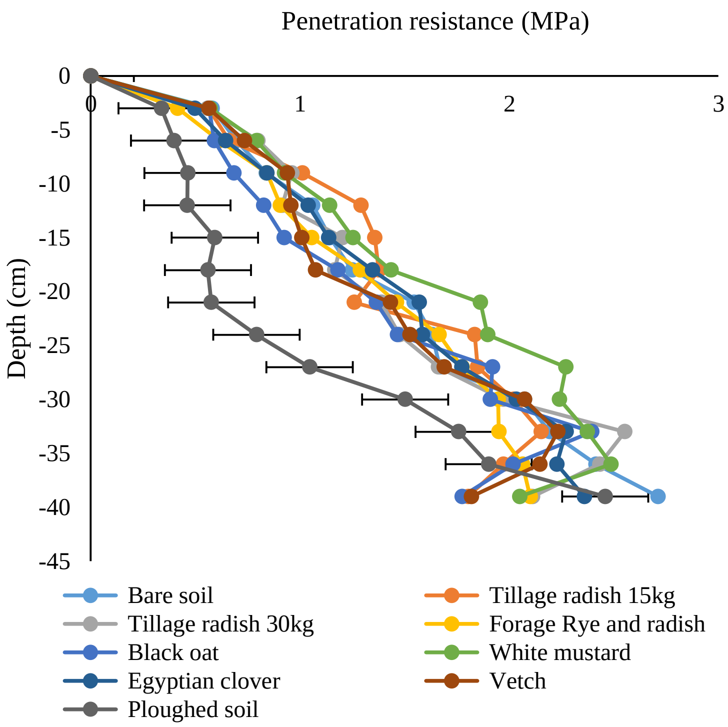


Figure 5.16 Penetration resistance from second field experiment in March 2018. Significant differences between treatments P<*0.001*. Error bars show LSD of 0.185

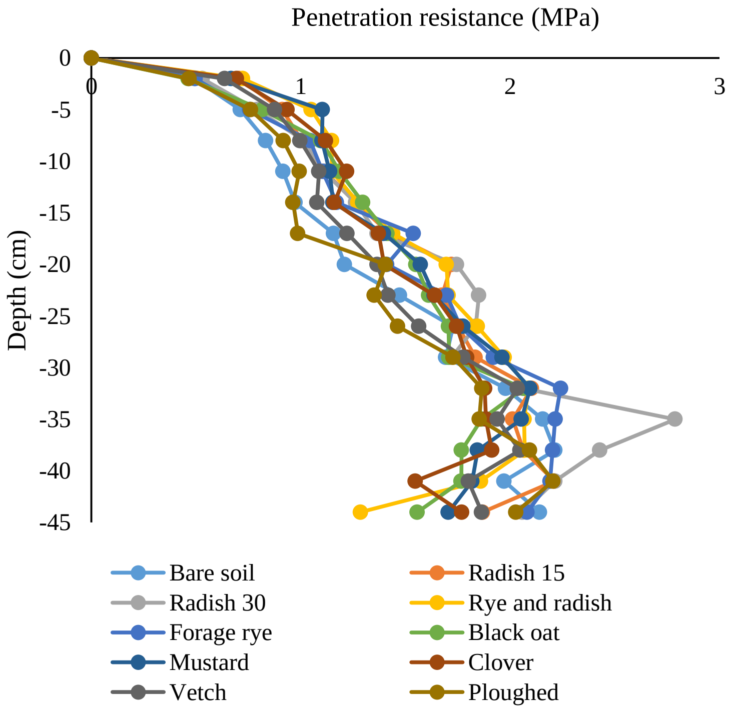


Figure 5.17 Penetration resistance from second field experiment immediately after sugar beet drilling on 17th May 2018. No differences between treatments.

5.3.3 Cover crop growth

5.3.3.1 Cover crop above ground biomass

In 2016, white mustard produced the largest quantity of above ground biomass followed by oil radish and tillage radish which produced the same quantity as one another (*$P<0.001$*). Forage rye and black oat produced the same quantity of biomass as one another but significantly more than Egyptian clover and vetch (Fig.5.18).

In 2017, treatments containing tillage radish or white mustard produced the greatest amount of above ground biomass but there were no differences within this group. Brassica cover crops, except white mustard, produced more above ground biomass than cereal and legume cover crops although this was not significantly more (*$P=0.069$*). There were no differences between cereal and legume cover crops in 2017 (Fig.5.19).

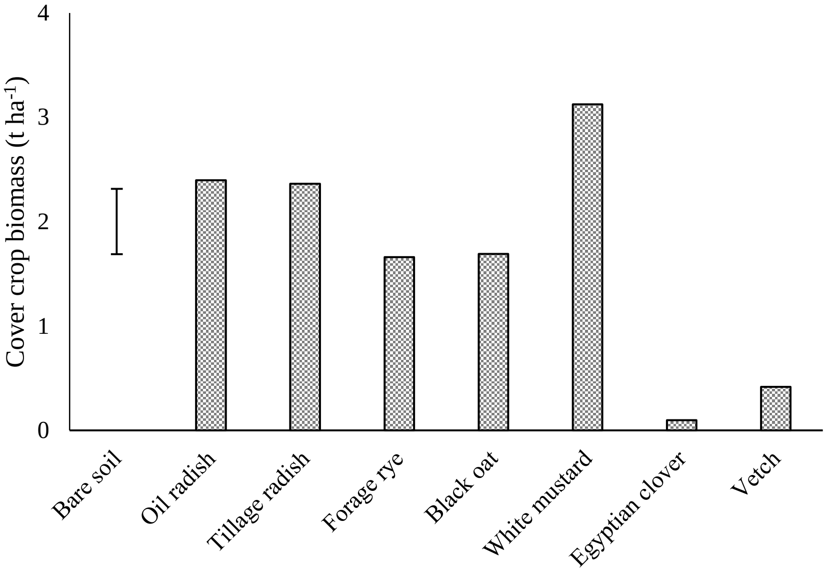


Figure 5.10 Cover crop above ground biomass in 2016. Significant differences between treatments $P<0.001$ error bars showing LSD of 0.62.

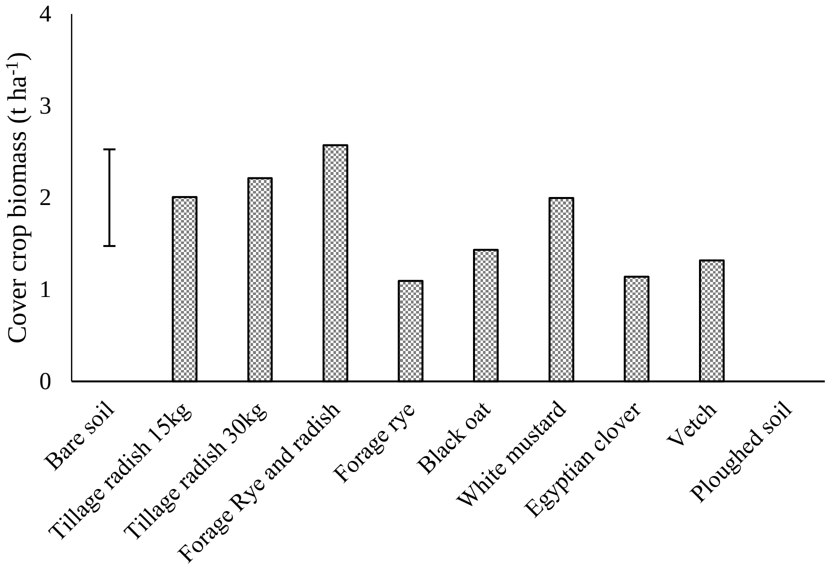


Figure 5.11 Cover crop above ground biomass in 2017. Near significant differences between treatments *P=0.069* d.f. 30 error bars showing LSD of 1.06.

5.3.3.2 Cover crop root growth

White mustard produced a higher root length density than all other treatments (Fig.5.20). All other cover crop treatments produced the same root length density. Despite the double seed rate for radishes sown at 30 kg ha^{-1} compared to radishes sown at 15 kg ha^{-1} there were no differences in root length density.

There was a positive linear relationship between root length density in November and the above ground biomass production in the first week of December (*P<0.001* Fig.5.21).

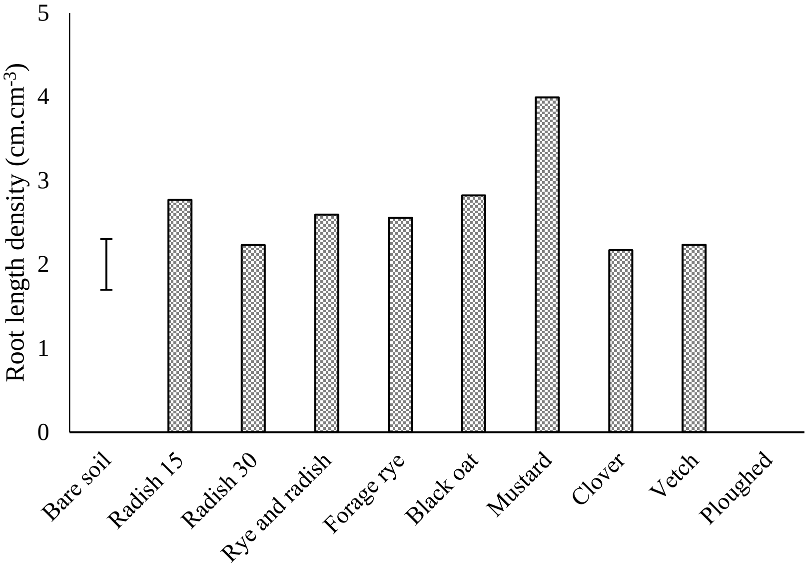


Figure 5.20 Root length density of cover crop experiment in November 2017. Significant differences between treatments *P=0.002* error bars showing LSD of 0.62.

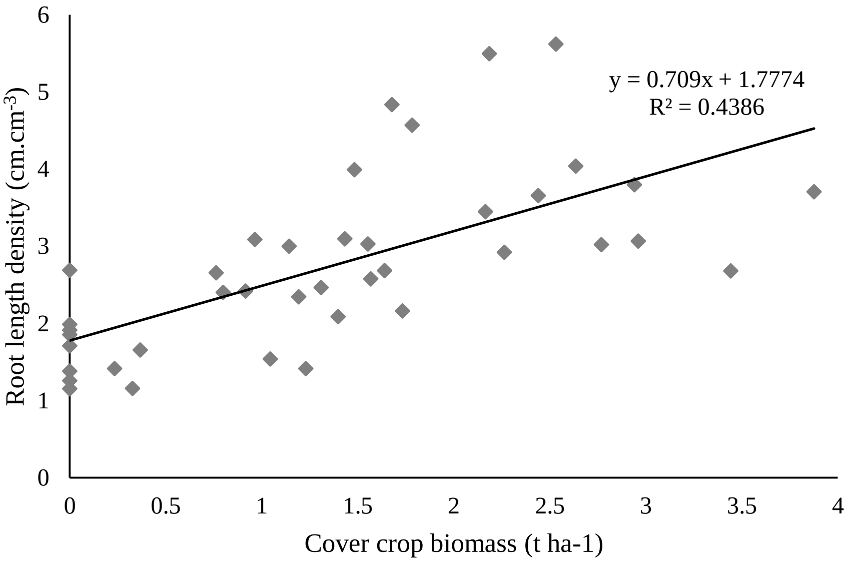


Figure 5.21 Linear relationship between cover crop root length density and cover crop above ground biomass production (*P<0.001*. d.f. 39)

5.3.3.3 Worm counts

In October 2017 no differences in worm population were observed. In November, ploughed soil had the lowest worm counts however this was not significantly less than Egyptian clover, tillage radish 30kg, bare soil, forage rye & tillage radish, vetch, forage rye, or mustard. Tillage radish 15kg had higher worm populations than the group mentioned previously however was not different to black oat (*P=0.05* Fig.5.22*)*.

In January, ploughed soil and bare soil had the lowest worm population. Forage rye and mustard had significantly more worms than ploughed soil and bare soil but none of the other treatments (*P=0.037*). Tillage radish 15kg and black oat resulted in more worms than ploughed soil but none of the other treatments. Vetch, tillage radish 30kg, forage rye & tillage radish and Egyptian clover were not significantly different to any other treatments (Fig.5.22).

Overall, ploughed soil showed a consistent trend for having the lowest worm population of all treatments.

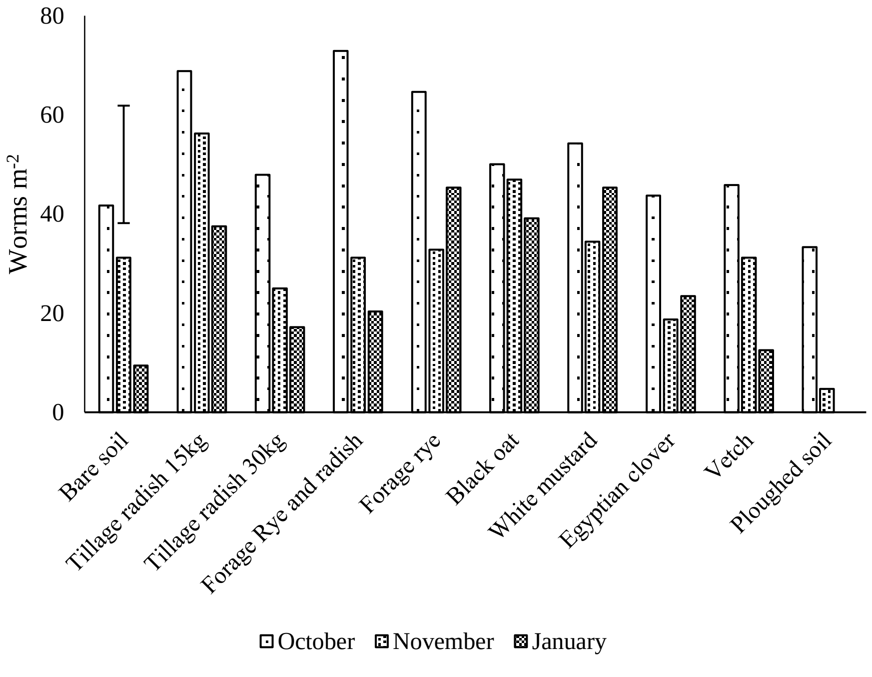


Figure 5.12 Worm counts from second experimental year in October, November and January. Significant differences between treatments in November and January *P=0.05 P=0.037* respectively, Error bar shows LSD between treatments (23.68)

5.3.3.4 Soil organic matter

No differences in soil organic matter were measured between treatments and the mean value for the whole experimental area was 5.9%

5.3.4 Sugar beet growth

5.3.4.1 Establishment

No differences in sugar beet establishment were measured in either year. However, the average sugar beet establishment was 100,656 plants ha^{-1} in 2017 and only 69,753 plants ha^{-1} in 2018 (Figures 5.23 & 5.24)

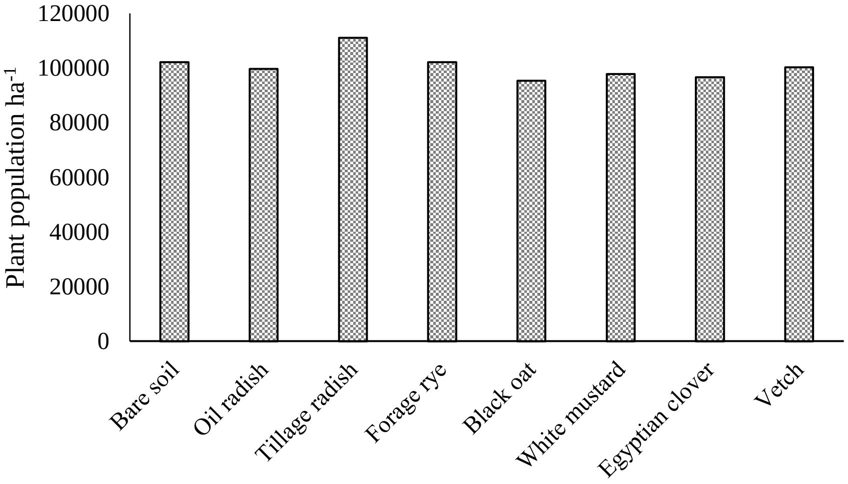


Figure 5.23 Sugar beet plant population per hectare 2017. No differences between treatments

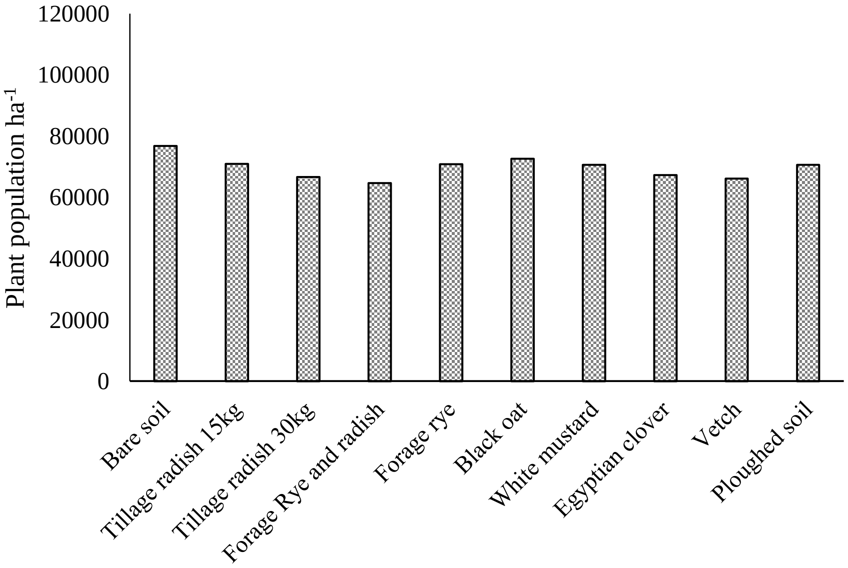


Figure 5.24 Sugar beet plant population per hectare 2018. No differences between treatments.

5.3.4.2 Sugar beet canopy cover

No differences in canopy cover between treatments were seen in either year. In 2017, maximum canopy cover was achieved at approximately 80 days after sowing (Fig.5.25).

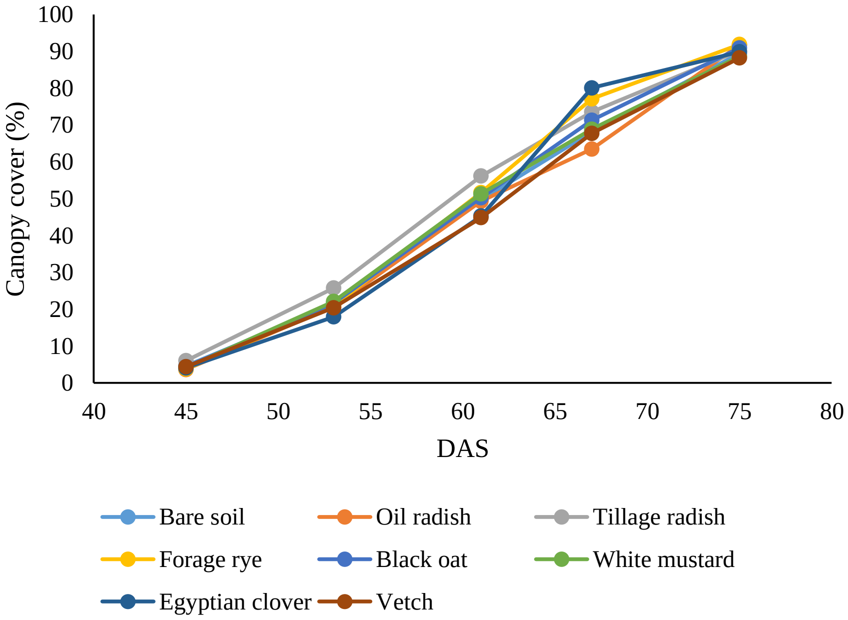


Figure 5.13 Canopy expansion of first experimental year. No significant differences between treatments. DAS = Days After Sowing

In 2018, canopy cover increased rapidly in the initial 48 days after sowing before it reached a plateau at approximately 50% ground cover. Canopy expansion occurred slowly between 48 and 76 DAS and maximum canopy expansion only occurred after 111 DAS (Fig 5.26).

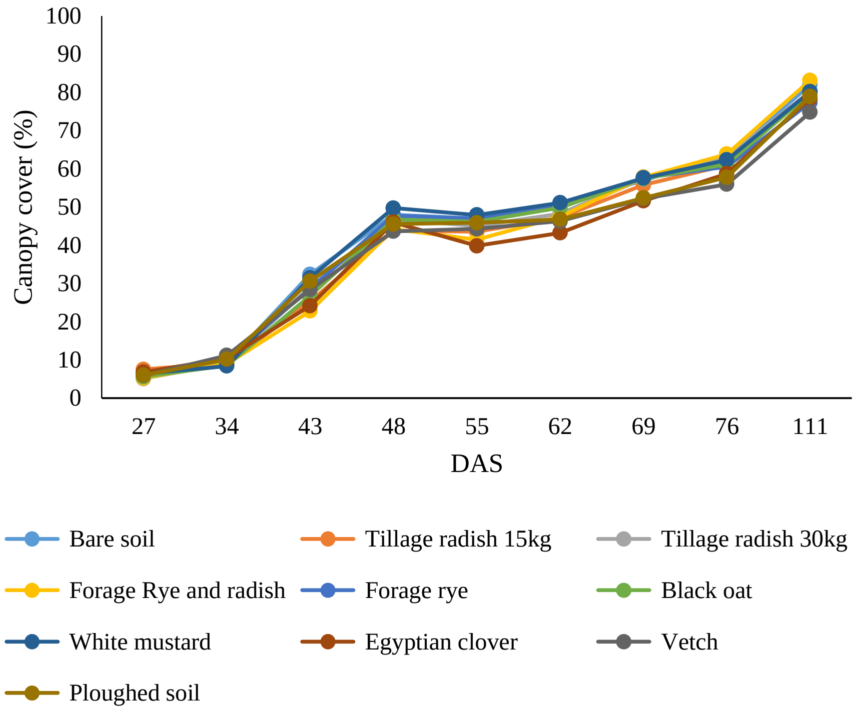


Figure 5.14 Canopy expansion of second experimental year. No significant differences between treatments. DAS = Days After Sowing

5.3.4.3 Sugar beet root fanging

No significant differences in root fanging were measured between individual cover crop treatments however when comparing sugar beet following cover crops or undistrurbed bare soil with sugar beet following the ploughed soil treatment there was a significant difference. Sugar beet following ploughed soil showed a significantly lower rate of root fanging than those that followed a minimum disturbance cultivation (*P=0.037* Fig 5.27).

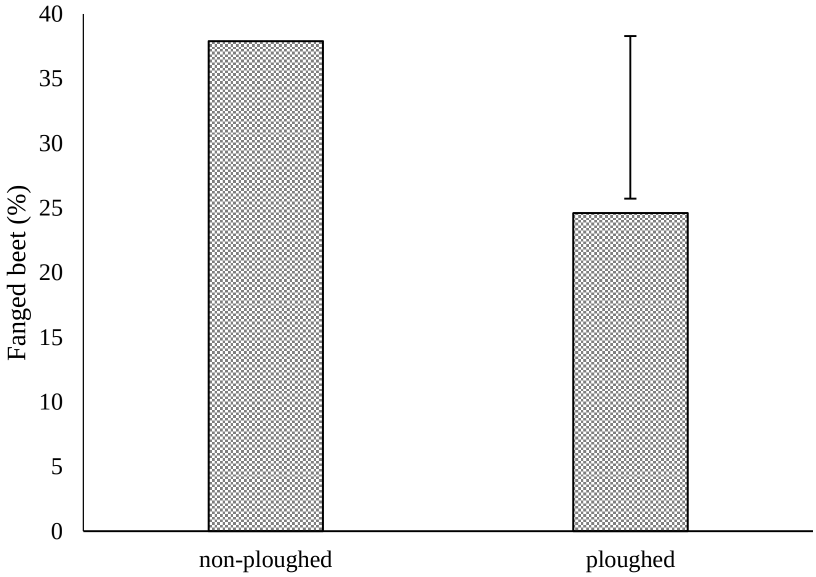


Figure 5.15 Percentage of roots that showed a high rate of fanging. Significant differences between ploughed treatment and all other treatments aggregated. *P=0.037* . Error bars showing LSD of 12.57.

5.3.4.4 Sugar yield

There were no differences in sugar yield between treatments in either year (Fig 5.28 & 5.29). Mean sugar yield in 2017 was 18.72 t sucrose ha^{-1} whereas in 2018 the mean sucrose yield was 11.73 t ha^{-1}.

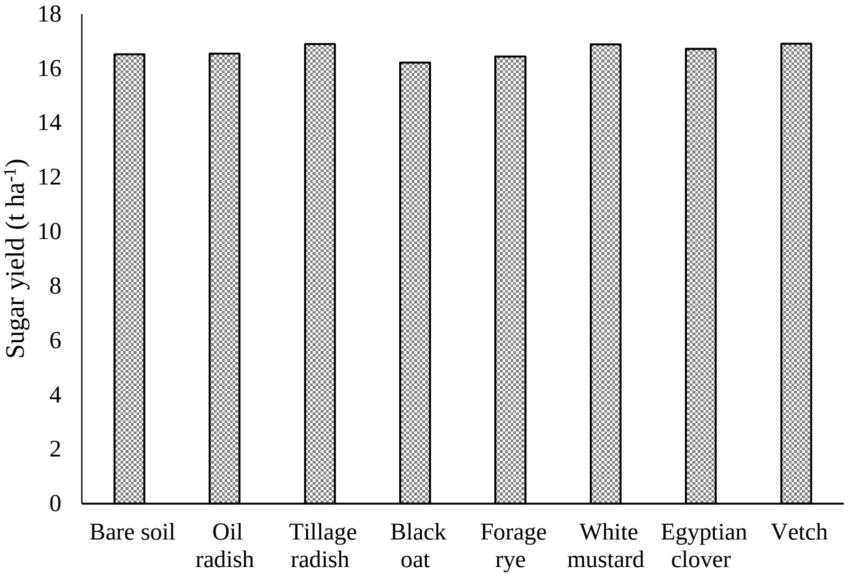


Figure 5.28 Sugar yield of first experimental year 2017. No significant differences between treatments.

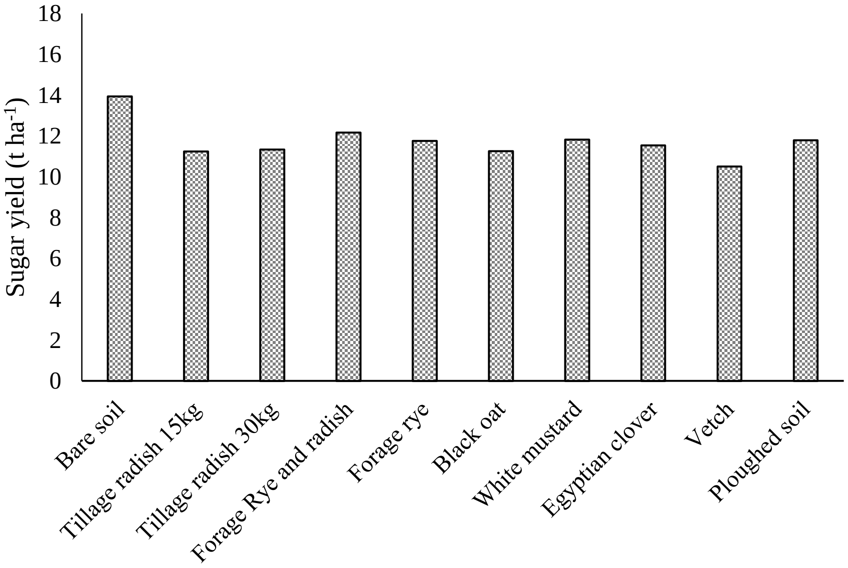


Figure 5.29 Sugar yield of second experimental year 2018. No significant differences between treatments.

5.3.4.5 Soil conductivity

Soil conductivity, where cover crops were grown, decreased throughout the autumn in both years. In 2016 this effect was significant between treatments with cereal and brassica cover crops resulting in lower soil conductivity than bare soil, Egyptian clover and vetch (*P<0.001* Fig.5.30). Soil conductivity increased between winter and spring where it peaked with no differences between treatments and then decreased as sugar beet growth occurred. No differences in soil conductivity were measured during sugar beet growth.

In the second year of experiments no significant differences in apparent soil conductivity between cover crop treatments were measured (Fig. 5.31). There was a slight increase in conductivity when comparing ploughed soil with cover cropped soil however the difference was not large. There was a trend for mustard, tillage radish and black oat to cause the greatest change in soil conductivity during cover crop growth but this was not statistically significant.

Change in soil conductivity was less following bare soil and ploughed soil compared to cover crops throughout cover crop growth but this was not statistically significant (Fig.5.31). This effect continued into sugar beet growth and there was a slight trend for soil conductance to change less following ploughed soil than cover crop treatments.

Treatments containing the brassica and cover crop species required a larger increase in soil moisture to reach field capacity in the spring following the cover crop (Fig 5.32).

In autumn 2016 there was a significant negative relationship between cover crop biomass production and soil conductivity (*P<0.001* Fig.5.32). The relationship was also significant in the second year of experiments however the relationship was not as strong (*P=0.003* Fig.5.33).

In October 2017 there was a positive relationship between soil conductivity in the top 50 cm of the soil profile and the worm population (Fig.5.34). In January, there was a positive relationship between soil conductivity in the top 50 cm of soil profile and worm population in treatments containing cover crops. In treatments without a cover crop there was a significant but small relationship between soil conductivity and worm population (Fig. 5.35).

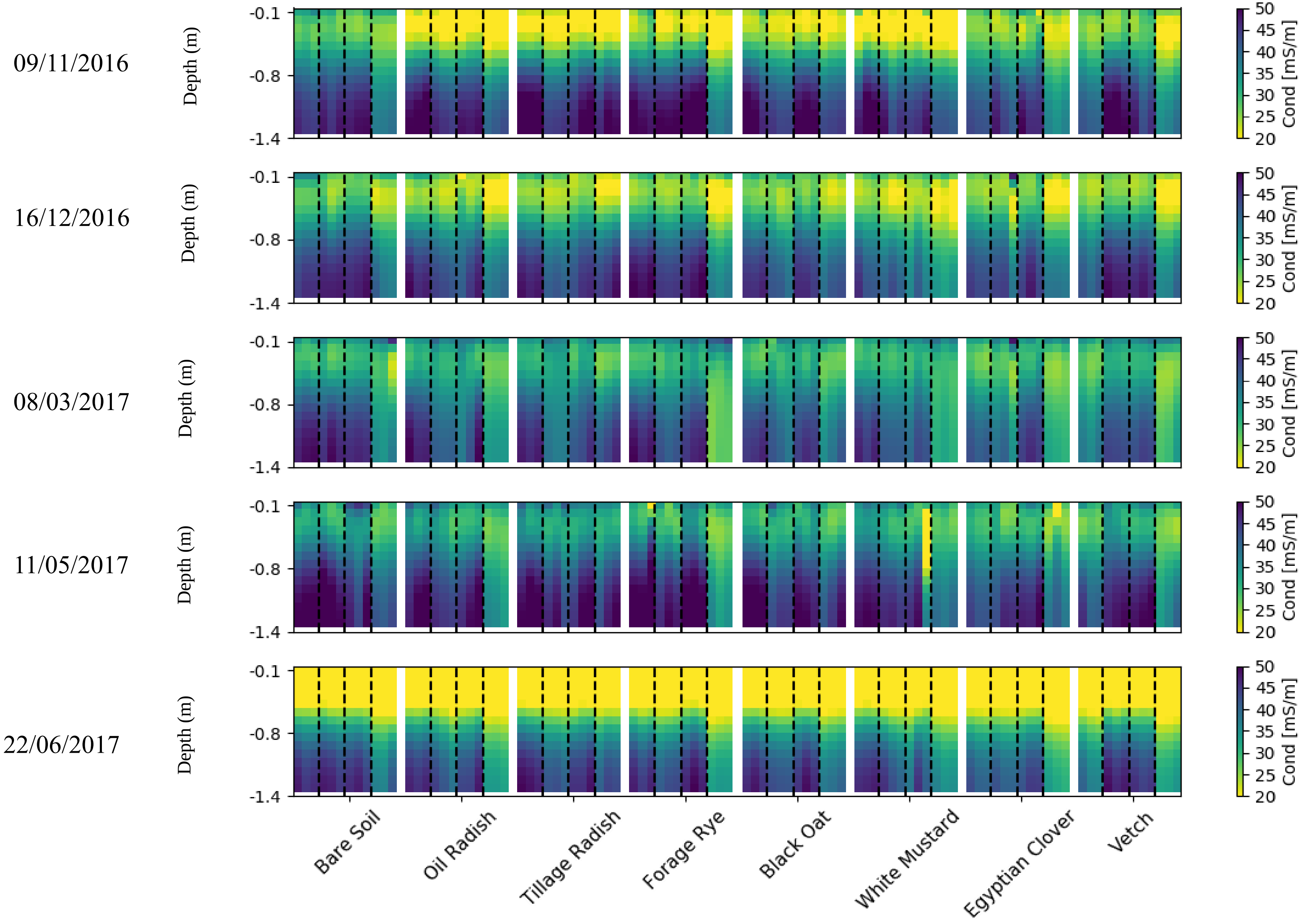


Figure 5.16 Inverted conductivity of first year of field experiments on individual dates from Autumn 2016 – Summer 2017 combining conductivity data from all depths

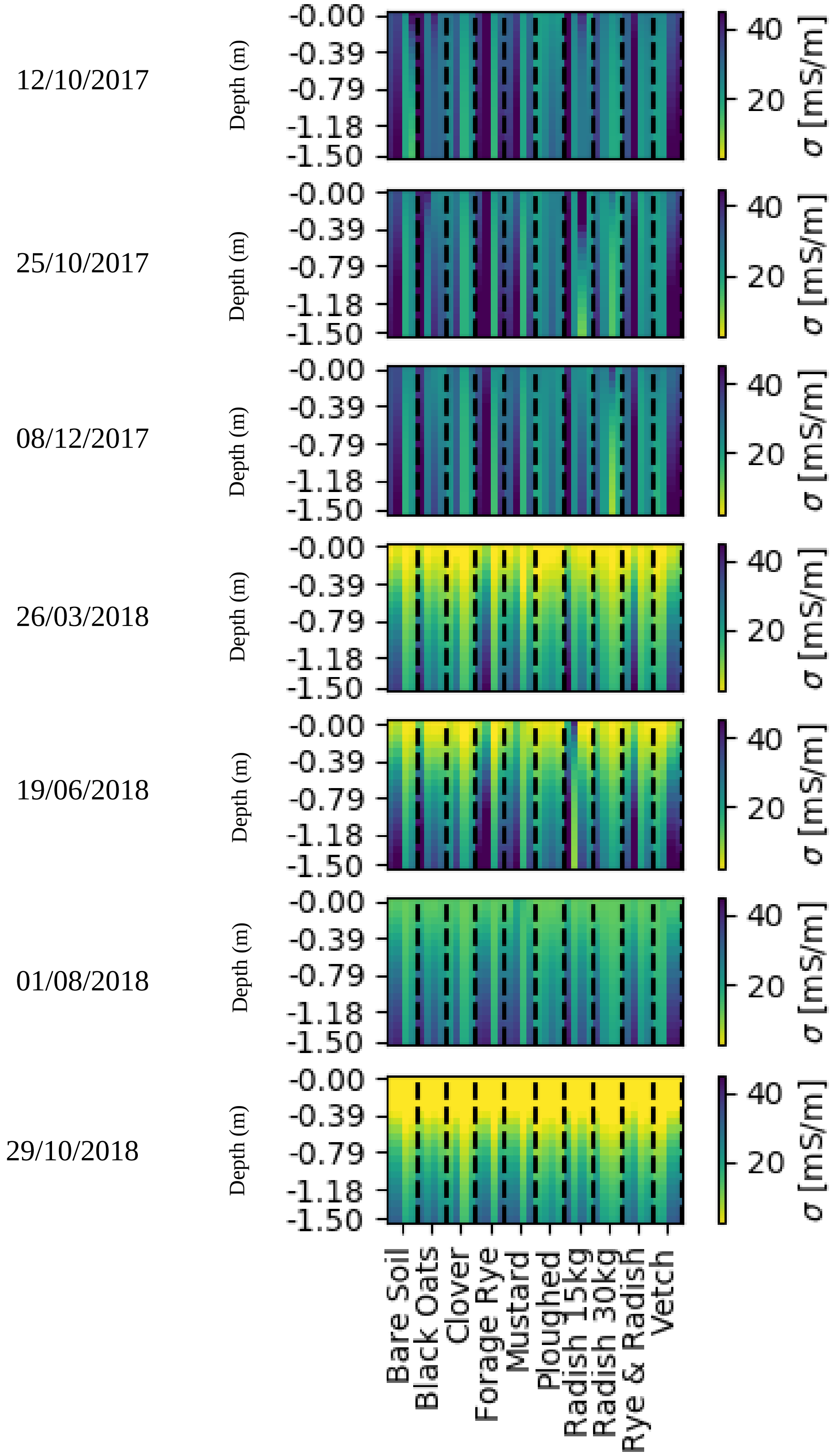


Figure 5.17 Inverted conductivity from the second year of experimentation with the scale standardised and all depths combined.. Colours indicate changes to soil conductivity with blue being more conductive and yellow being less conductive

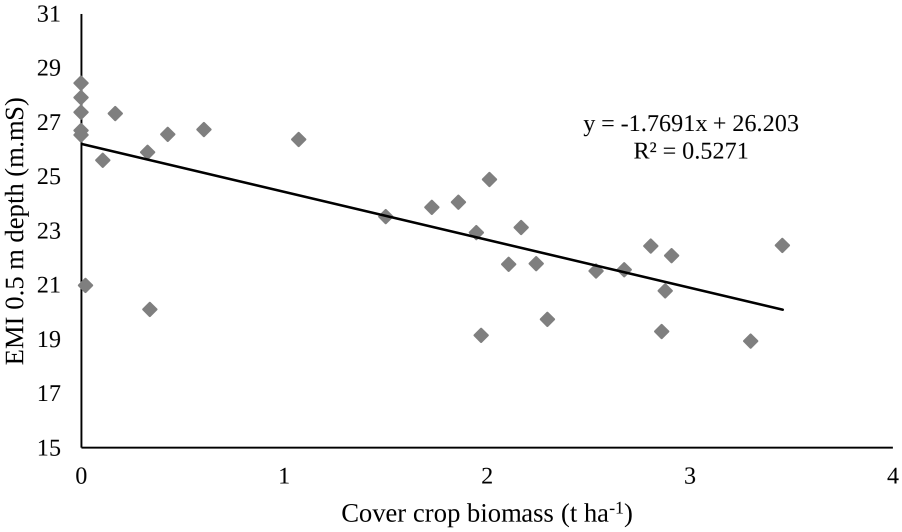


Figure 5.32 Relationship between EMI in December 2016 and the above ground biomass of cover crops (*P<0.001*. d.f. 31).

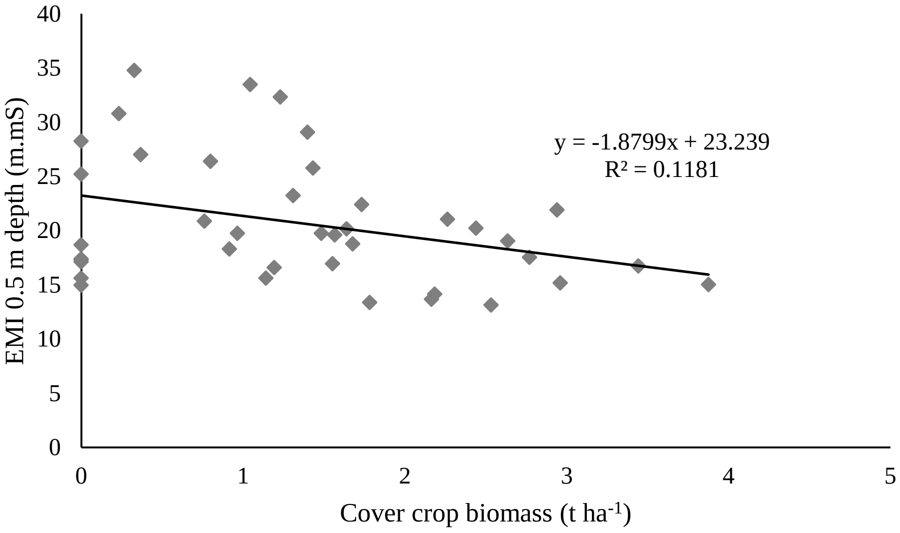


Figure 5.33 Relationship between EMI in December 2017 and above ground biomass of cover crops (*P=0.003*. d.f. 39)

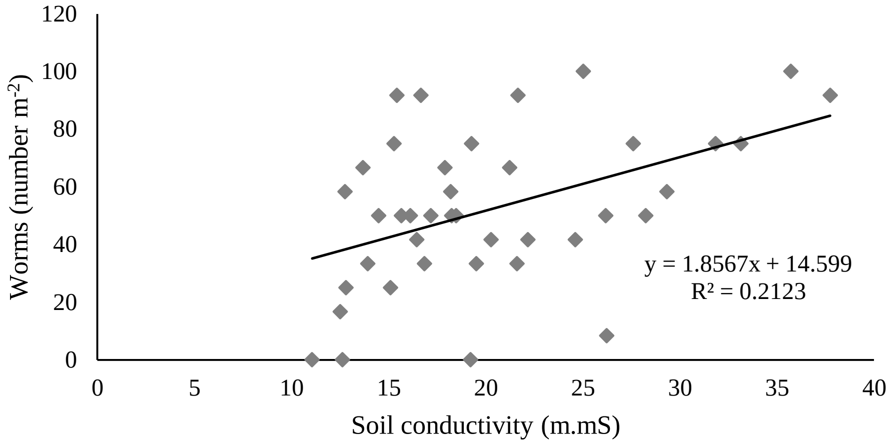


Figure 5.34 Relationship between October Conductivity at 0.5m depth and earthworm population (*P=0.003* d.f.39.)

A significant negative relationship between EMI in June and the proportion of sugar beet that were fanged was seen (*P<0.001* Fig. 5.36) showing that as soil moisture increased the risk of sugar beet fanging decreased. There was a significant interaction between EMI and the presence of cover crops showing that the positive relationship only occurred when the cover crops were present.

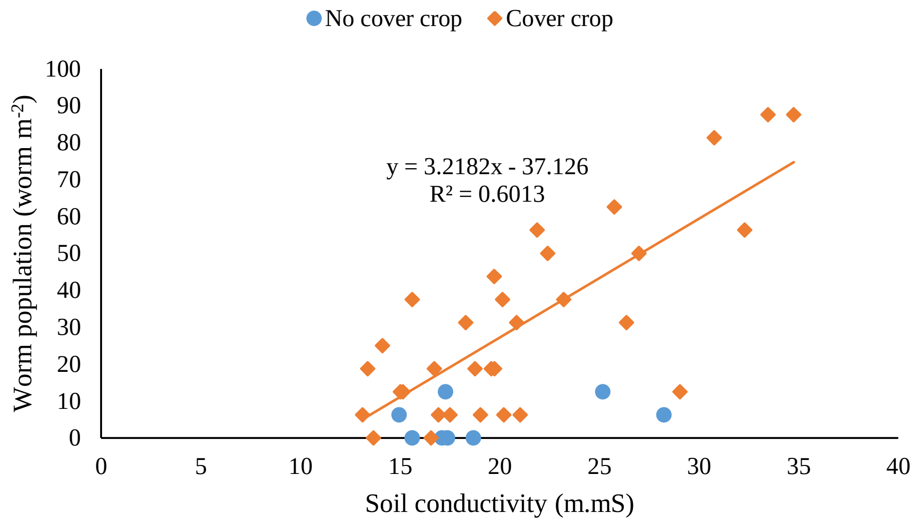


Figure 5.35 Significant relationship between soil EMI and worm population January when cover crops were present (*P<0.001)*

Positive relationships between changes in EMI and canopy cover and sugar yield were identified showing that greater reductions in EMI between March and October resulted in larger canopy size and higher yield (Figures 5.37 & 5.38, 5.39).

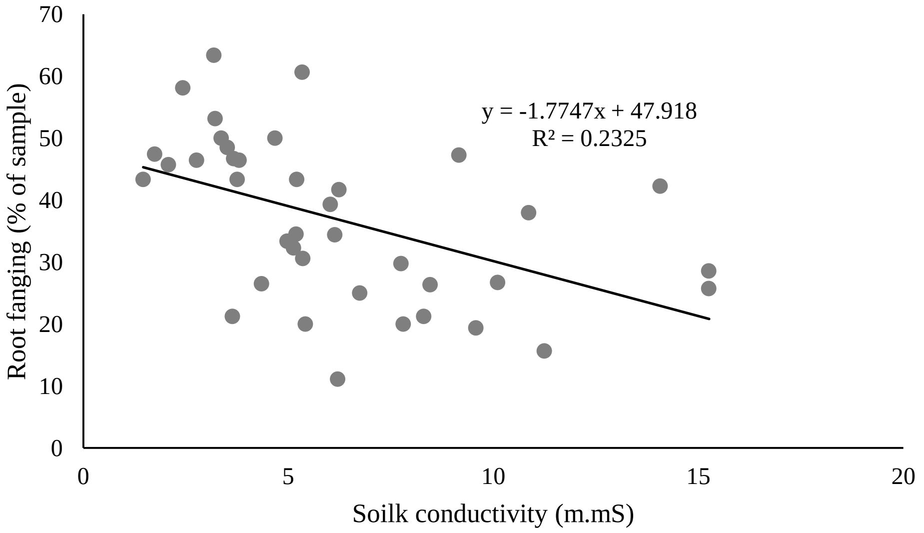


Figure 5.36 Relationship between soil conductivity in June 2018 and the proportion of sugar beet roots that became fanged (*P=0.002*, d.f.38).

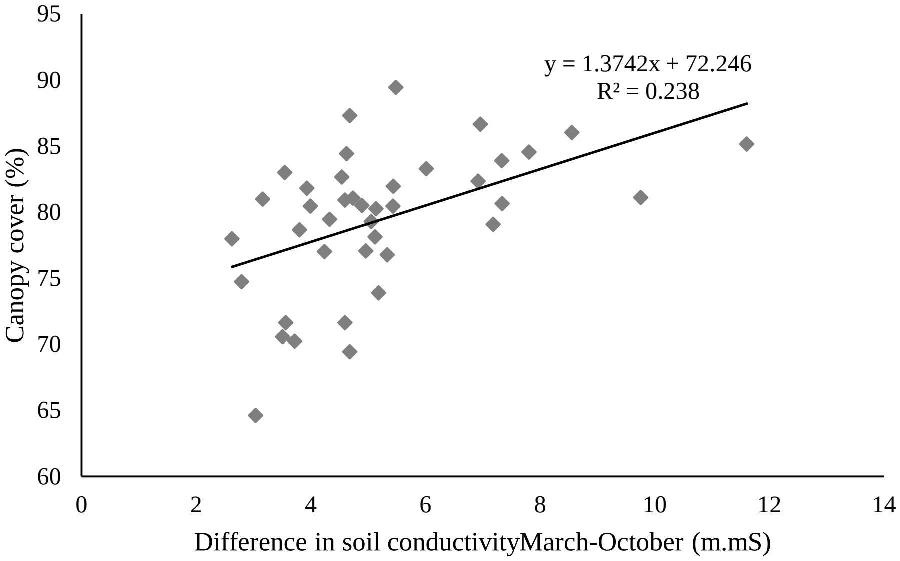


Figure 5.37 Relationship between change in soil conductivity between March and October and canopy cover in October (*P=0.001* d.f. 39).

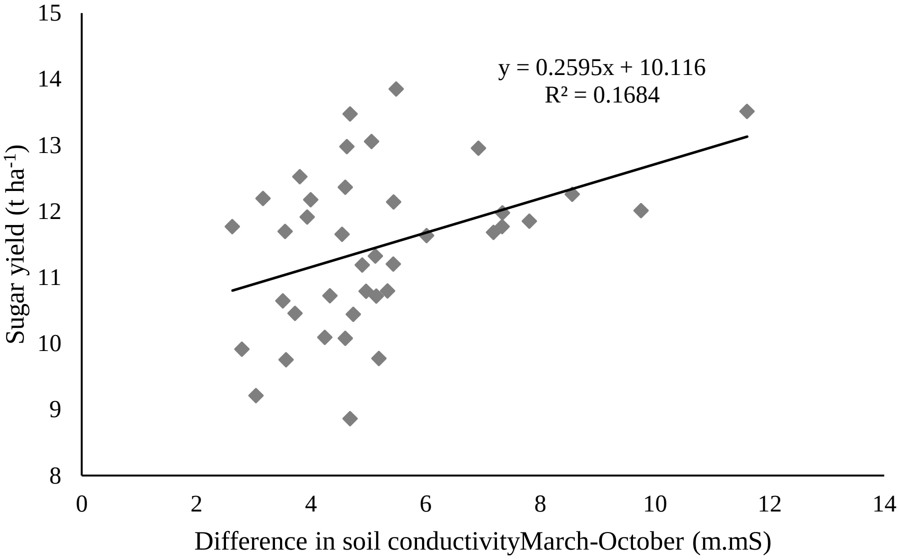


Figure 5.38 Relationship between change in soil conductivity at 0.5 metres depth from March-October and the final sugar yield (*P=0.009*. d.f. 39).

5.4 Discussion

5.4.1 Soil structure

Growth of autumn sown cover crops in temperate regions is governed by water availability at drilling and accumulated thermal time during establishment. It has been suggested that cereal crops are more sensitive to thermal time whereas brassica crops are more sensitive to soil moisture (Allison et al., 1998a). When moisture and temperature are not limiting, the growth of cover crops will be dependent on the growth habits of particular species (Laine et al., 1993). In September 2016, neither water nor thermal time were limiting for the cover crops. In both years, the brassica cover crops produced the greatest quantity of above ground biomass with white mustard producing significantly more than the radish treatments. This was followed by the cereal cover crops and finally by the legume cover crops. In 2018, there was a reduction in the biomass produced by the cereal cover crops which is likely to be explained by a period of cool temperatures in the first two weeks after cover crop drilling. Mustard is a long day flowering plant (Kinet, 1972) and immediately produced flowering organs on the top of a long stem. Radish cover crops, on the other hand, remained in a vegetative state throughout their growth. The above ground biomass produced by radish was mainly restricted to leaf production whereas in mustard a considerable proportion of above ground biomass could be attributed to the production of a woody stem. All other cover crop species require a period of vernalisation prior to reproductive growth and therefore remained in vegetative growth for the duration of the experiment until destruction.

A significant relationship between above ground biomass and soil moisture suggested that transpiration of the cover crop during the autumn was able to reduce soil moisture. This was measured on the soil surface and also throughout the soil profile. It has been suggested that this drying effect may have negative implications for aquifer refill which would normally happen during the autumn and winter (Allison et al., 1998a). However, it is possible that a drying effect on the soil profile may also prevent damage to the soil structure that frequently occurs when soils undergo tillage in sub-optimal soil moisture (Dexter and Bird, 2001, Patterson et al., 1980). It is also possible that the reduction in soil moisture during the autumn may result in lower water availability for the following crop.

There was a significant positive relationship between above ground biomass and root length density of treatments in autumn 2017. This shows that there is evidence to suggest that to achieve the maximum root colonisation of the soil profile a cover crop with greater leaf biomass is preferable. Chapter 4 suggested that black oats produce more roots per unit of shoot which may be beneficial to maximising the influence of roots on the soil profile while reducing the residue that needs to be removed before establishment of the following crop. It was impossible to measure the root:shoot within the field however, it is important to highlight that timing of cover crop destruction in December was to allow sufficient time for all cover crop residues to degrade prior to sugar beet establishment. It is possible that if less time was given for decomposition of cover crop residues, there would be a trade-off between cover crop root growth and the ability to remove excess crop residues. Furthermore, decisions surrounding removal of residue would also depend on preferred method of cultivation. Cogman and Morris (2009) suggested that it is not the quantity of residues that have implications for sugar beet establishment, rather it was the position of the residues in the soil profile that had the greatest effect on sugar beet establishment. This suggests that as long as cover crop residues are sufficiently removed from impeding the sugar beet seedlings, cover crops that maximise above and below ground biomass are preferable.

It is frequently suggested that the inclusion of cover crops in a rotation in the place of either fallow or a stale seedbed also provides a winter food source for soil invertebrates. Stroud et al. (2017) found that it is unlikely for short term cover crops to lead to immediate increases in deep-burrowing earthworms due to the relatively long time period necessary for generations to regenerate. It has been suggested that epigeic and endogenic earthworm populations respond more rapidly to short term increases in food supply (Leroy et al., 2008). This suggests that cover crops that produce the greatest biomass could lead to the highest earthworm populations. It is possible that a result of the drying effect that the cover crop biomass had on the soil profile may have negative effects on earthworm movement and abundance. This may be more likely in cover crops that produce more above ground biomass as they appear to have a greater effect on soil drying. The positive relationship between EMI at 50 cm depth and the earthworm population at 20 cm depth suggests that earthworm abundance is dependent on soil moisture. As the cover crops have dried the soil profile, it is likely that earthworms have followed the moisture gradient both horizontally and vertically to areas of the soil that are more favourable to them. However, it is possible that when cover crops coincide with periods of high rainfall ideal conditions are created where earthworms have a plentiful food source and sufficient moisture however, this scenario was not measured.

The relationship between soil conductivity and earthworm population in January showed that, in the presence of a cover crop, the earthworm population was positively affected by increasing soil conductivity. This did not appear to be the case for non-cover cropped treatments. This suggests that cover crops are able to be used as a food source by earthworms but this is made more difficult by dry soil conditions. It also appears that low worm population in ploughed soil is as a result of a lack of food source rather than the inversion of the soil, as there were no differences between bare soil and the ploughed soil treatment. Previous studies have suggested that ploughing is more detrimental to earthworm populations than fallowed soil alone (Peigné et al., 2009, Barnes and Ellis, 1979). However, this experiment suggests that the absence of a suitable food source was the most important factor.

The role of cover crops in improvement of the soil structure is largely dependent on the ability of the system to increase bio-pores through the soil profile (Haruna et al., 2018, Breland, 1995). Large connected pore space has been linked to improved water and air infiltration and reduced soil strength which may improve plant growth. Connected pore space is created by the movement of roots through the soil profile and by earthworm activity as they burrow in vertical and horizontal directions. While it has been suggested that pore space created by roots may be able to withstand more force than pores created by roots (Blackwell et al., 1990) it is a combination of the roots and earthworm activity that result in the greatest production of biopores. Therefore, it is counterproductive for a cover crop to result in a reduction in earthworm activity. However, the minimised disturbance of the soil during cover crop growth and the increased chance of winter rainfall make this unlikely to be the case.

Despite the large differences in cover crop biomass production, rooting, and earthworm activity, there was insufficient evidence to suggest that the cover crops had a significant impact on the soil structure as a whole. It has been suggested that the production of root mucilage from cereal cover crops in particular are able to bind soil particles resulting in an aggregate size distribution with a greater proportion of small macro aggregates (Dexter and Bird, 2001, Breland, 1995). Furthermore, there is evidence to suggest that the tap-rooted cover crop species may be able to break apart large soil pans however this has not been measured in this experiment (Chen and Weil, 2010).

In neither experimental year were differences in aggregation observed. It is possible that this may be as a result of the soil texture which was a sandy loam with only 15.6% clay. The clay content of a soil is likely to be a key factor of aggregation due to their ability to have greater cohesion between soil particles and the behaviour of clay during wetting and drying cycles (Wagner et al., 2007). It is possible that, despite the rigorous growth of the cover crops in both years of experiments the relatively high sand content of the soil type resulted in no differences in soil aggregation. It is possible that changes to the soil aggregation may be achieved on soils with a high sand content however this is likely to be as a result of long term effects of plant roots rather than short term cover crops (Abdollahi and Munkholm, 2014).

Root sampling during cover crop growth suggests that treatments containing tillage radish may be capable of creating larger biopores than most other cover crop species. Treatments containing tillage radish produced significantly more roots with a diameter of greater than 1.5 mm. It is possible that roots with a larger diameter will increase the size of biopores produced but also produce biopores with greater structural integrity as they cause the greater compression of the soil immediately in contact with the root sheath (Blackwell et al., 1990).

The effects of biopores on overall porosity has been suggested to be positive. However, measurements of the soil surface bulk density suggest that, despite the increase in roots as a result of the cover crops, there was no difference in porosity with the exclusion of the ploughed treatment. It is likely that, as seen in Chapter 3, the presence of roots changed the pore distribution rather than the overall soil porosity. As a result there may have been some changes to the location of pore space within the soil profile however, there was no overall increase in total porosity. Pore connectivity has not been examined in this experiment however, previous studies suggest that conservation agriculture techniques such as long term reductions of inversion tillage are able to increase pore connectivity over a number of years (Azooz and Arshad, 1996). There is little evidence to suggest that the effects of cover crop roots on pore connectivity occurs within a single season of growth.

Soil surface conditions are highly related to the success of sugar beet establishment. Sugar beet seedlings are drilled to a stand of approximately 100,000 seeds per hectare using precision drilling techniques (Jaggard, 1979). It is important for 95% of these seeds to establish into mature plants in order to maximise light interception which is directly related to sugar yield (de Koeijer and van der Werf, 1995, Scott and Jaggard, 1993b). In order to maximise establishment the seed must be placed in a seedbed that allows good seed-soil contact, generally has a high porosity and has low restraints to root growth. In addition, sugar beet establishment has been shown to be improved by light compression post-drilling (Arvidsson et al., 2012). No differences were seen in aggregate size distribution suggesting that no treatment would result in better seed-soil contact. In the second year of experimentation there was a reduction in shear strength and penetration resistance as a result of the ploughed treatment. It may have been expected that this would result in better sugar beet establishment in this treatment. However, no differences were measured. It is possible that due to the low soil moisture content at drilling the entire experiment was at suboptimal soil moisture content. It is likely that this also explains the reduction of mean sugar beet population from 100,000 plants per hectare to 60,000 plants per hectare from 2017 to 2018.

5.4.2 Sugar beet growth

In the first year of experimentation rapid sugar beet growth occurred. Despite sugar beet drilling occurring after the optimal period of March, all treatments achieved 90% canopy ground cover by mid-June. Rapid canopy expansion and maximum ground cover increases the potential yield of the crop as a result of intercepting the greatest quantity of photosynthetically active radiation (PAR). There were no differences in sugar beet canopy expansion between cover crop treatments suggesting that conditions were optimal for crop growth. It has been suggested that nitrogen taken up by cover crops in the autumn may become available to the following crop. It has been shown that cover crops do release nitrogen after destruction however there is a lag period between cover crop destruction and the availability of the nitrogen due to the decomposition which is governed by the carbon-nitrogen ratio (Cicek et al., 2015). Cicek et al. (2015) also suggested that nitrate release rate is less than the nitrate demand from field crops. Furthermore, nitrogen is used by sugar beet only to provide rapid and maximal canopy growth and therefore requires fertilisation immediately after seedling establishment (Milford et al., 1985a). Therefore, it is unlikely that slow-released nitrogen from cover crops would be available rapidly enough to supply the crop canopy. There is some evidence to suggest that decomposition of cover crops in the spring may also reduce nitrogen fertiliser availability of the soil if the carbon-nitrogen ratio is too heavily weighted towards carbon. This has been recorded in rye cover crops which can denitrify the soil of nitrogen fertiliser temporarily to allow decomposition of biomass. The lack of differences between treatments in either year suggests that this did not occur and the nitrogen supply from fertiliser was not affected by the cover crops.

Water availability also has a significant effect on canopy expansion. Water is used in the plant for substrate transport from the roots as well as driving the osmotic gradient to the leaves allowing transpiration and photosynthesis to take place. In the early summer this allows the production of a large leaf canopy able to intercept the majority of incident radiation. Later in the season, after the development of the 12th leaf, the plant switches to partitioning products from photosynthesis to the root producing the storage root (Milford et al., 1988, Werker et al., 1999). In 2018 the late drilling date of the experiment resulted in lower plant population which is likely a result of poor moisture availability for germination. The short period between sugar beet drilling and the onset of the drought conditions in June, July and August did not allow sufficient growth of the juvenile plant as reflected by the slow canopy expansion. The sugar beet canopy did not achieve 90% ground cover until early autumn and therefore a considerable amount of PAR was not captured by the crop. The high temperatures of the summer also resulted in considerable water stress and wilting of the canopy. This is likely to have caused damage to the leaves as they were subjected to being dried out completely by the sun leading to early onset senescence (Ober et al., 2005).

Previous studies have speculated that biopores created by cover crop roots may allow better access to water during the growing season (Jakobsen and Dexter, 1988, Henderson, 1989). However, the lack of differences between cover crop treatments in the 2018 experimental season suggest that there was neither a benefit to cover crop inclusion nor a negative effect of ploughing.

The lack of differences in yield between treatments in both years suggest that weather conditions during the growing season had a greater effects on yield than the cover crops. The 2017 sugar beet growing season could be considered almost ideal for crop growth and allowed an optimal plant population followed by optimal growing conditions. Conversely, the late drilling and sub-optimal seedbed moisture of 2018 resulted in poor crop establishment. The drought conditions of the summer resulted in sub-optimal growth of the canopy and poor PAR interception which is the likely reason for a difference of approximately four tonnes of sugar per hectare.

Depending on the species, cover crop growth was 20-40% lower in 2017 than 2016. It is possible that if the cover crop growth had been similar in autumn

2017 to 2016 there would have been a greater effect on cover crops on the soil profile which may have resulted in differences in sugar beet growth. We have seen in previous chapters that cover crops may result in changes to sugar beet rooting and the production of biopores from cover crops have been linked to greater water availability to cereal crops (Jakobsen and Dexter, 1988). Therefore, it is possible that cover crop root growth in 2017 was insufficient to have a lasting effect on sugar beet growth.

5.4.3 Soil conductivity

In the first year of experimentation the cover crop species had a significant influence on soil conductivity to a depth of 1 metre. The brassica species white mustard, oil radish and tillage radish resulted in the largest reduction in soil conductivity during coiver crop growth followed by the cereals, and then the legume species. The most likely explanation of changes to conductivity is the moisture of the soil influenced by the water uptake by plants, a phenomenon seen in wheat cultivars (Whalley et al., 2017).

The largest differences in soil conductivity between treatments was seen in the layers closest to the soil surface. It is likely that this is the area of the soil where the cover crops will have had the greatest influence as the roots are more likely to have depleted soil moisture in the layers closest to the soil surface. The differences in conductivity were also seen throughout the profile. Firstly, this may be as a result of roots being present at this depth and accessing the water from the deeper layers of the soil profile . It is possible that this may be explained by the rooting habits of taprooted species that have the ability of growing deeper than lateral rooting species. It has been found previously that water uptake will occur preferentially in the shallow layers of soil before being depleted from the deeper soil profile (Fitters et al., 2017). Furthermore, cover crop growth in the UK has been shown to be limited due to the cool autumn temperatures and low moisture availability at drilling which makes it unlikely that rooting from any species will have taken place at a depth of over one metre. It is therefore more likely that, as suggested by Allison et al. (1998a), cover crops reduce the quantity of autumn/winter rainfall that is able to percolate through to the groundwater.

The differences in conductivity and inferred soil moisture is likely to be driven by above ground biomass of the cover crops. The greater amount of above ground biomass, the greater the transpiration rate of the plant resulting in greater water depletion from the soil. There was a close negative relationship between cover crop above ground biomass and soil conductivity during the autumn. Larger crop canopies are likely to increase the lag period between precipitation falling and the infiltration to the soil profile due to the water adhering, temporarily to the canopy. This will give additional time for water to be evaporated from the crop canopy further reducing the soil moisture content of the soil.

Further to the relationship between the size of canopy and soil moisture content, brassica cover crops have been shown to continue to transpire at temperatures lower than cereal species. This suggests that water use, even if small, is likely to continue through the winter if cover crops are not destroyed. In this experiment, after cover crop destruction, differences in soil moisture and conductivity reduced between treatments. It is likely that the removal of growing plants allowed rainfall to recharge the soil profile to field capacity prior to the spring.

The lack of differences measured in the second year are a likely result of a number of factors. Firstly, as mentioned previously, the growth of cover crops will be dependent on thermal time accumulated. This will be particularly important in the weeks immediately following cover crop drilling as radiation reciepts will also be highest at this point. The thermal time accumulated during cover crop growth in both seasons was extremely similar however in autumn 2017, the cover crops received slightly less thermal time in September than in the previous year. It is possible that this period is critical to establishment of the cover crop canopy and may be the reason for differences in biomass production between the two years.

The smaller effect of cover crops on soil conductivity in 2017 compared to 2016 is likely to be a result of the 100mm higher rainfall received in autumn 2017. As measurements of soil conductivity are greatly affected by soil moisture it is possible that the differences in cover crop growth would not have been realised using this technique to the same degree as the previous season (Shanahan et al., 2015, Whalley et al., 2017). It is likely that the slightly reduced cover crop growth and the increased rainfall during autumn are the reason why measurements of soil conductivity were not so conclusive in the second year of the experiment. Despite apprent measurements appearing to show a lesser relationship between cover crop growth and soil conductivity in 2017, the differences between dates show that the relationship is still there but is masked, slightly, by the increased rainfall.

Soil conductivity was continually measured throughout sugar beet growth in both experimental years. No differences between treatments were recorded in either year of experimentation. This suggests that the cover crops did not have a long term effect on the soil moisture. It is possible that if their growth had continued there may have been differences in the available water for the sugar beet. This phenomenon was more likely to have been measured during 2018 as the drought of the early summer caused great water stress in the sugar beet. However, in 2018 there was also a period of four months between cover crop destruction and sugar beet establishment as the cold conditions of March and April 2018 made it impossible to establish the sugar beet crop. It is likely that this period of time allowed the experimental area to become less variable than it was immediately after the cover crop growth thus reducing the apparent differences in soil moisture and conductivity.

Soil conductivity (EMI) was closely related to sugar beet growth and yield. In 2018, there was a strong correlation between soil conductivity in June, July and August with the final yield of the plots. The higher the conductivity during the early summer the greater the yield in the autumn. This suggests that plots that had a greater conductivity indicated better water availability to the sugar beet crop. During the drought, better water availability is likely to have allowed greater transpiration. It is likely that relatively greater transpiration will have resulted in more assimilation and sugar yield (Sinclair et al., 1984). Using the EMI data from the sample point closest to sugar beet drilling, and comparing that to subsequent sample dates, we are able to calculate the differences in EMI between dates. Over time EMI decreased therefore suggesting we can use this as a proxy for water use by the sugar beet crop. Plots that had the greatest difference in EMI between sample dates also had the largest canopy cover at each point. The same relationship was seen between difference in EMI and final sugar yield. This suggests that EMI was able to show the water uptake of the crop during the drought and relate that directly to the sugar yield. Differences in EMI were not seen between treatments and therefore it is likely that the differences in water availability were caused by subtle differences in soil texture rather than the effects of cover crops. The soil texture will determine the water availability to the crop, which in conditions such as the drought of 2018, will have a heightened effect on sugar yield (Fredlund and Xing, 1994).

The relationship between soil conditions and sugar beet root morphology was clear in the second year of experiments. Root morphology was not significantly different between individual treatments suggesting that there was no effects of cover crops on sugar beet root shape. However, there was a significant increase in the fanging of sugar beet roots in plots that were not ploughed compared to those that were.

Sugar beet root fanging has been strongly linked to physical constraints in the soil as well as infestation by free-living nematodes (Koch, 2009). It is unlikely that there was any interaction of the sugar beet with free-living nematodes as previous cropping has not favoured the build up of nematode populations and the clay content of the soil is unfavourable for their movement. Therefore it is likely that fanging can be blamed on soil conditions. Lipiec et al. (2003) suggested that increased soil strength prevents sugar beet taproots from forming a singular root apex as they are prevented from moving vertically through the soil profile. The relationship in the unploughed treatments suggest that as EMI and inferred soil moisture increases the proportion of fanged roots decreases. It is likey that this is also linked to the soil texture. It is known that soils with a higher water content have lower strength and resistance. Therefore soils with a higher moisture content are less likely to result in root fanging. When soil strength is too great roots split into two or more fangs. Fanging of the root increases the likelihood of root breakage during harvest, reducing yield of the crop, and increases the proportion of soil that is attached to the root. Soil loss from the field has negative implications for the environment as a contribution to soil degredation as well as a financial penalty from sugar processors who see excess soil as a waste product. The risk of sugar beet fanging as a result of soil moisture and EMI will be determined by soil type. At low soil moistures, clay soils in are likely to result in large soil clods which have a high aggregate stability (Patterson et al., 1980, Norton et al., 2006). In contrast, sandy or loamy soils, although being dry, will have aggregates with less stability which are less likely to cause root fanging.

In addition to the use of EMI as a means of explaining crop growth and sugar beet root morphology, it may also provide a useful tool for agricultural decision makers. As EMI is able to pick up differences in soil moisture throughout the profile, it is possible to create a map of agricultural fields that highlights areas that are prone to drought or flooding which may allow a more targeted approach to deep soil cultivations and long term management of compaction and soil moisture. It is possible that this may be useful in future years as the UK is likely to experience more variable climatic conditions where rainfall is less predictable and in drought cponditions water needs to be conserved and in high rainfall years, soil erosion needs to be avoided (Collins et al., 2014).

5.5 Conclusion

In conclusion, from the two years of experimentation, on this soil type none of the cover crop species tested resulted in a change to the soil structure. This suggests that we should reject sub-hypothesis 1a that rooting characteristics, and therefore species have an effect on soil structure. This may suggest that the changes to structure reported by some may be dependent on the soil texture, the long term tillage regime and the growing period of the cover crop thus is it impossible to accept sub-hypothesis 1e. Unexpectedly, it appeared the growth of cover crops reduced earthworm activity. It is likely that this is due to the drying effects that the cover crops had on the soil profile and may not be an indication of long-term earthworm populations in response to cover crop inclusion in the crop rotation. This suggests that we should consider accepting sub-hypothesis 1c and 1d as the water availability and use by the cover crop had an effect on the soil conditions during cover crop growth. The lack of differences between treatments mean it is unlikely that sub-hypothesis 1a can be accepted.

It is also apparent that the growth of the sugar beet, when nutrition and crop protection is accounted for, is limited mostly by water availability during the growing season suggesting that we have further evidence to accept sub-hypothesis 1c. There was no benefit to sugar beet water uptake as a result of the cover crops confirming that we should reject sub-hypothesis three at least in this experiment as sugar beet growth was unrespoinsive to cover crop presence. No differences in growth were seen as a result of the cover crops with the exeption an increase in root fanging where the strength of the soil profile was limiting to tap-root growth.

Measurements of soil conductivity showed that it is capable of detecting differences in the moisture of the soil profile as a result of autumn sown cover crops. EMI is also able to give an indication of water use by sugar beet. Futhermore, this indicates we can accept that cover crop water uptake has an effect on their impact on the soil conditions as suggested in sub-hypothesis 1d which will in part be determined by air temperature and water availability as suggested in sub-hypothesis 1b and 1c. Measuring soil conductivity may be a useful tool in mapping agricultural fields to plan for areas where water may be limiting to crop growth and may allow decision makers to take action to remediate soil restrictions where possible.

Measurements of soil conductivty also revealed that the effect of cover crops on soil moisture is determined by their type and size and that large cover crops, which tended to be brassicas in this experiment, had the greatest drying effect on the soil profile.

Chapter 6: The effects of cover crops on subsequent sugar beet crops on commercial farms in the UK

6.1 Introduction

The previous chapters have focussed on the effects of cover crops in fully replicated experiments. This was useful for minimising variability and to understand the fundamental effects of cover crops on soil structure and sugar beet growth. However, the ability to conduct experiments on commercial sugar beet farms allows a greater understanding of their use and effects on multiple soil types and in different management regimes.

UK sugar beet cultivation is limited to Lincolnshire and East Anglia. Due to variation in soil texture, it is important to quantify the effects of cover crops on typical soils used for UK beet production. Spatial variability of soil, rotational and soil management regimes vary greatly between individual farms (Townsend et al., 2016). Therefore, this chapter and comparisons to previous chapters will allow us to evaluate sub-hypothesis 1e which aims to understand whether the impact of cover crops is determined by soil texture.

Soil conditions of farms and fields are highly dependent on the tillage and crop rotation of a farm. In turn, the crop rotation and tillage will be greatly dependent on the soil texture. Typically, a UK arable crop rotation will centre on the cultivation of a cereal crop (Jennings and Fuller, 2003). Often this is winter wheat which will be managed for animal feed or milling for human consumption. Some growers on light textured soil with low rainfall, however, favour barley for its relative drought tolerance due to earlier flowering in the summer (Shavrukov et al., 2017). Prevention of cereal weed, pest and disease accumulation is partially achieved by having a diverse crop rotation with non-cereal break crops such as oilseed rape (*Brassica napa*), or field beans (*Vicia faba*) (Jennings and Fuller, 2003) on stoney or clay soil. On free-draining, sandy or organic soils it is commonplace for potatoes (*Solanum tuberosum*), carrots (*Daucus carota*) and onions (*Allium cepa*) to be grown in the crop rotation (Jennings and Fuller, 2003). Decisions to grow vegetable crops tend to be as a result of soil type suitability whereas the cultivation of sugar beet is often undertaken due to the proximity of a sugar factory, and the traditionally favourable gross-margins. As a result sugar beet production occurs across a wide range of soil types in East Anglia.

The growing season of sugar beet offers the ideal period of time between cereal crop harvest, in August, and sugar beet establishment, after March, when an autumn sown cover crop could be established. Similarly, catch crops, established in the autumn to absorb residual nitrate prior to winter are often considered an option by farmers. It has been shown that catch crops are effective at reducing nitrate loss during their autumn growth (Cooper et al., 2017, Shepherd, 1999). As a result catch crop use has gained popularity with farm based decision makers, environmental policy makers and water companies. It is likely that increasing awareness of environmental issues such as eutrophication and soil health may result in subsidised or compulsory inclusion of over-winter cover crops.

Previous experiments have suggested that cover crop growth can alter soil aggregation and influence soil moisture and worm populations with no impact on sugar beet yield (Chapters 2, 3 & 4). However, these findings have been as a result of experiments conducted on a relatively narrow soil textural range, and in conditions that have been set up to simulate commercial field conditions. Due to the diverse range of soil types used for sugar beet production, it is therefore important to examine the effects of cover crops on soils that are part of long-term management practices and are close to standard industry practice for sugar beet cultivation.

To complement the experiments conducted at Sutton Bonington Campus, on a sandy loam soil, two further experimental sites were chosen in the sugar beet growing areas of Norfolk and Suffolk. Holkham Farms, in Norfolk, is based on loamy sand and the second site at Shimpling, Suffolk is based on the Hanslope soil series which is a loam. Challenges of the light textured soil were mostly as a result of ensuring adequate moisture was available to the sugar beet crop and avoiding drought conditions. The texture of the soil allows for easy preparation of a sugar beet seedbed (Hakansson et al., 2006). The clay soil site allowed for monitoring where soil conditions may cause more challenges to provide a sugar beet seedbed due to the tendency for soil to remain wet during the spring leading to a higher risk of cloddy seedbeds (Norton et al., 2006). Soil management of the two sites differed as a result of the varying conditions. Tillage at Holkham is widely based on a minimum-tillage system in order to avoid loss of moisture and organic matter from the soil profile. In contrast, the tillage regime at Shimpling was broadly an autumn plough based system which was in place for control of blackgrass and to provide the finest seedbed in the spring.

Responses of the crops are likely to be highly dependent on both soil texture and soil management which will be difficult to separate. As a result, results will primarily be compared within an experimental site before overall findings are compared between the two sites.

Comparisons between the two years will also allow some understanding of the influence of air temperature and moisture availability on cover crop success and the effects they have on the subsequent sugar beet as suggested in sub-hypothesis 1b and 1c.

The comparison between two separately located field sites and the soil texture will also give the opportunity to compare the water availability following a cover crop on a clay soil and a sandy soil.

6.2 Materials and Methods

6.2.1 Holkham

Holkham Farms situated in North Norfolk, near the town of Wells-next-the-sea, is based largely on a loamy sand soil (sand 76%, silt 21%, clay, 3%). Three years of field monitoring was carried out on this farm September 2015-October 2018 which included three full seasons of cover cropping and sugar beet cultivation. The second year of field monitoring September 2016 - October 2017 has been excluded due to mechanical hoeing removing a substantial proportion of the sugar beet following cover crops thereby invalidating the results. The first experiment comprised a split field design where part of the field was drilled with an oil radish (*Raphanus sativus*) cover crop in September which was grazed with sheep, for one month, in the following January. The second split of the field was over-winter stubble which was not tilled until the spring. In the third season the field was split into three areas. Two areas were drilled with an oil radish cover crop. One of the cover cropped sections was sprayed with glyphosate in February 2018, the second cover cropped section was grazed by sheep in January (Table 6.1). As with the first year, there was an over-wintered stubble section of the field.

The cover crop at Holkham was established using a minimum tillage cultivator which cultivated the top 10 cm of the soil profile and spread the cover crop seed directly onto the freshly cultivated soil. In both years digestate from an anaerobic digester was applied to the whole trial area in the October following cover crop establishment.

Table 6.1 Overview of cover crop treatments, drilling dates and harvest dates of sugar beet at Holkham and Shimpling

		Cover crop					Sugar beet			
Location/Year	Over-winter treatment	*Latin name*	Variety	Seedrate (kg ha^{-1})	Drilling date	Destruction date	Drilling date	Harvest date	Drilling rate (units ha^{-1})	Variety
Holkham 2015/2016	Stubble	n/a	n/a	n/a	n/a	n/a	10/04/2016	22/09/2016	1.2	BTS755
	Oil radish (grazed)	*Raphanus sativus*	Siletta Nova	15	01/09/2015	07/02/2016				
Holkham 2017/2018	Stubble	n/a	n/a	n/a	n/a	n/a	18/04/2018	02/11/2018	1.2	BTS860
	Oil radish	*Raphanus sativus*	Siletta Nova	15	02/09/2017	08/02/2018				
	Oil radish (grazed)	*Raphanus sativus*	Siletta Nova	15	02/09/2017	05/01/2018				
Shimpling 2017/2018	Bare soil	n/a	n/a	n/a	31/08/2017	01/02/2018	10/05/2018	04/10/2018	1.2	KWS Sabatina
	Tillage radish	*Raphanus sativus*	Mino	15						
	Forage rye	*Secale cereale*	Protector	55						
	Black oat	*Avena strigosa*	Pratex	35						
	Egyptian clover	*Trifolium alexandrium*	Tim	15						

Immediately prior to sugar beet drilling, the same cultivator used to drill the cover crops, was used to create a seedbed for the sugar beet crop. After seedbed preparation, the sugar beet were drilled to a stand at a rate of 120,000 seeds ha^{-1} in rows of 50 cm wide. In the first season, the area was sown with a sugar beet variety that was tolerant to beet cyst nematode (*Heterodera schactii,* BCN) due to concerns of BCN infestation. In the second season the area was sown at the same rate with a conventional variety as there was limited risk of BCN infestation.

Due to the lack of replication, each area was sampled in a stratified way by using the 'W' method of sampling across each treatment strip. Data was analysed by Genstat 19th edition mostly using the t-test method and regression analysis. Data was checked for normality and homogeneity of variance during analysis using Genstat.

6.2.2 Shimpling

The second field site was located in Shimpling, Suffolk on the Hanslope soil series which is a loam soil with high silt content (sand 28%, clay 24%, silt 48%). At this field site a field experiment ran from September 2017 - October 2018. The field experiment was arranged in a randomised block design with four blocks of five treatments. Treatments included tillage radish (*Raphanus sativus*), rye (*Secale cereale*), black oat (*Avena strigosa*), Egyptian clover (*Trifolium alexandrium*) and an over-wintered ploughed treatment. Prior to cover crop establishment the field had been part of a conventional plough-based arable rotation and the previous crop was winter wheat which was harvested in July 2017. To establish the cover crop, the area was firstly ploughed to remove soil restrictions in the soil surface and cover crops were drilled with a Lely combination drill on 31 August 2017. The area was rolled immediately after drilling to prevent excess moisture loss due to the relatively high September temperature.

Cover crops were left to grow from September 2017 to February 2018 when they were sprayed with glyphosate. To establish a seedbed for the following sugar beet, the area was cultivated using a single pass of a power harrow immediately prior to sugar beet drilling. Sugar beet were drilled at a rate of 120,000 seeds ha^{-1} with a row spacing of 50 cm on 16 May 2018.

At both sites, in both years, sugar beet were treated as per standard farm practice. Each crop received 120 kg N ha^{-1} equivalent as ammonium nitrate. Pest, weed and disease control was carried out in conjunction with local agronomists.

6.2.3 Measurements during cover crop growth

6.2.3.1 Bulk density

Bulk density and soil moisture were measured on 30/08/2015, 11/11/2015 and at Holkham 05/03/2018 by taking samples of the soil surface using a standard 140cm^{3} bulk density ring. Samples were weighed wet, dried and weighed again to calculate gravimetric water content and bulk density in g cm^{-3}.

5.2.3.2 Penetration resistance

Penetration resistance of the soil was measured using a Rimik CP40II cone penetrometer. Readings were taken at Holkham on 30/08/2015, 11/11/2015, 11/04/2016 and 19/04/2018. At Shimpling readings were made at drilling on the 10/05/2018. At each sample location, three insertions were completed. From the data average values were taken for every three cm depth which were then averaged between the three insertions. Between September 2017 and October 2018 the penetrometer data was limited due to problems with the equipment.

5.2.4.3 Aggregate size distribution

At each date samples of approximately 500g soil was sampled from each location within the field to a depth of 20 cm. Samples were air dried in the lab until a constant weight was achieved. Samples were then passed through a stack of sieves with the apertures of 10 mm, 6 mm, 5 mm, 4 mm, 3 mm, 2 mm, 1 mm, 500 µm, 50 µm & 20 µm. Samples were shaken manually for 30 seconds and each aggregate class weighed. Data was used to produce an aggregate size distribution for each sample location over time. Measurements of aggregation were made at Holkham on the 03/03/2016, 18/04/2016. At Shimpling measurements were made on the 03/03/2018 and the 10/04/2018.

6.2.5 Measurements during sugar beet growth

6.2.5.1 Establishment and population

Sugar beet plant population was measured at each site when plants had reached two true leaves. At Holkham this was achieved by taking 10 positions across each treatment strip on a map before seeing the field area. At each point five metres was measured using a tape measure. The beet plant population was counted in four rows, two rows either side of the tape measure, to give a population of sugar beet $10m^{-2}$. For the Shimpling field trial this was repeated but $10m^{-2}$ was measured using the same method in the middle of each plot.

6.2.5.2 Canopy growth

During canopy expansion from drilling until harvest, % canopy cover was assessed. This was achieved using a modified method described in Wright et al. (2018). Images from above the crop canopy were taken using a Canon 80D with a 10-18 mm lens on which was suspended by hand 1m above the canopy. Three images were taken of each plot on each sample date. Canopy cover was measured using colour thresholding of each image using ImageJ to determine green area (Rasband, 2011) by selecting the areas of the photographs which were within the colour range for leaves. At Shimpling measurements were taken on 17/06/2018, 14/07/2018, 19/07/2018, 26/07/2018, 22/08/2018, and 05/09/2018. In the first year at Holkham this was done on the 27/06/2016, 11/07/2016, 01/08/2016. In the second season this was done on the 14/05/2018, 14/06/2018, 26/06/2018, 03/07/2018, 09/07/2018, 03/08/2018, and 14/09/2018.

During the drought conditions of June 2018 measurements of the canopy temperature using a Flir C2 thermal camera and canopy greenness using a SPAD meter were taken on 28 and 29 June at Holkham and Shimpling respectively. Measurements were taken at 10am on each day and it was ensured that cloud cover was similar for each measurement. Photos were taken of each plot using the thermal camera which were then analysed using the Flir tools software to ensure only measurements of the crop canopy were taken and soil temperature was not measured. Within each plot five plants were randomly selected for SPAD measurements. On the largest fully expanded sugar beet leaf an average SPAD value was taken from five readings from each plant and recorded.

6.2.5.3 Sugar beet growth and yield

Destructive measurements of sugar beet growth were planned for July 2018 prior to storage root expansion however, drought conditions made this impossible at Shimpling as roots could not be removed from the soil. Leaf samples of $2m^2$ were taken from each plot at the Shimpling field site for biomass analysis and leaf nitrogen content as measured using the DUMAS method (Sweeney and Rexroad, 1987). Destructive measurements of leaf biomass and root biomass were taken at Holkham in 2018 where $2m^2$ at five locations in each strip were harvested and dried at 70^oC until a constant weight was achieved.

Samples were taken for sugar analysis at each site on the 22 September 2016 (Holkham) and 22 October 2018 (both sites). At Shimpling $3m^2$ sugar beet were lifted and the leaves were removed and fresh weight recorded before being discarded. At Holkham five locations were chosen on a map prior to seeing the field, in each strip in both years, $1m^2$ of beet were lifted and topped before being assessed for root fanging then bagged. Root samples were analysed for sugar content at the British Beet Research Organisation (BBRO) tarehouse as soon as possible after harvest.

6.2.5.4 X-ray Computed Tomography

At sugar beet harvest, intact cores of the soil profile were taken at five points across each section, in a “W” arrangement. Soil cores with the dimensions length 20 cm, diameter 5 cm were inserted by hand into the soil profile. The soil around each core was removed using a shovel and the cores were removed intact without disturbing the soil profile within. Cores were wrapped in clingfilm and then stored upright at 3^oC until scanning.

Soil cores were scanned using a VTomex scanner by GE Inspection Systems at the University of Nottingham Hounsfield Facility, Sutton Bonington Campus at a resolution of 40µm. Reconstruction of the scanned images was done using the software Volume Graphics 2.2 and scans were exported into image stacks for analysis in ImageJ. In ImageJ, image stacks were black and white thresholded by eye for pore space and % pore space was recorded. The images were also thresholded inversely for soil matter and % soil was recorded. An average value was calculated as pore space per slice. Pore space in individual slices was combined to calculate the mean value for each centimetre. Data from each depth was then analysed and compared between the treatments.

6.2.7 Statistical analysis

Data was analysed using Genstat 19th edition. Shimpling field site and controlled glasshouse experiment were analysed using general ANOVA and regression analysis. At Holkham, field experiments were analysed using t-test analysis. Where ANOVA analysis was used means were compared using the least significant difference calculated from all treatments. Where t-test analysis was used errors and differences were compared using standard error of means (SEM) which was calculated as the square root of the standard deviation of the mean.

6.3 Results

6.3.1 Holkham 2015 – 2016

6.3.1.1 Penetration resistance

Penetration resistance was consistent across the field site in August 2015 prior to the harvest of the winter wheat crop. Penetration resistance increased gradually with depth (Fig 6.1). Penetration resistance in November 2015 was lower in the top 10 cm of soil where a cover crop had been established (P=0.01, Fig.6.2). Between 10 cm and 20 cm the penetration was increased with cover crop growth. Below 25 cm penetration resistance was greater in the stubble strip (Fig 6.2). Between August and November overall penetration resistance decreased. Penetration resistance in the sugar beet crop, after seedbed establishment, was not significantly different between the two treatment strips.

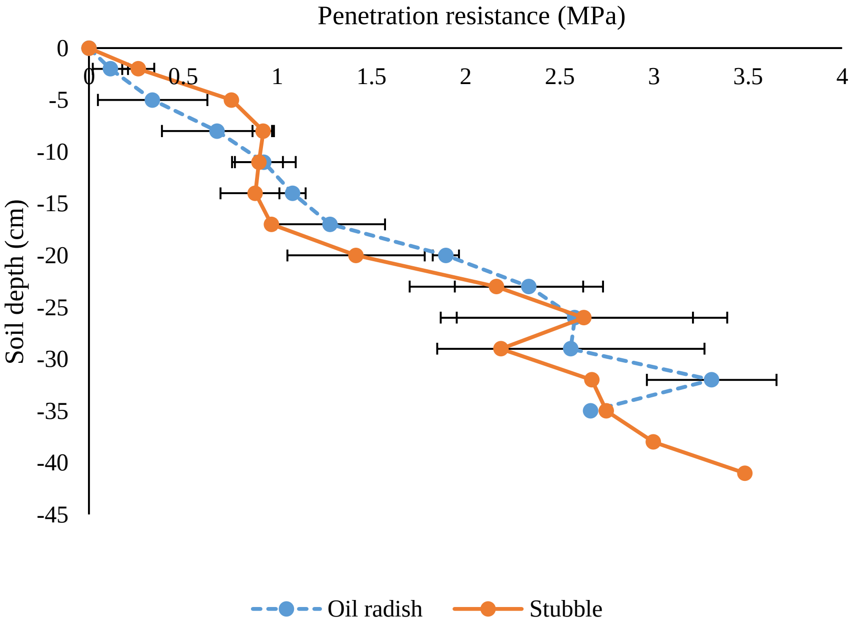


Figure 6.1 Penetration resistance of field site in August 2015 prior to cereal harvest. Error bars show standard error of means at each depth. At this point the labels refer to cover crop treatment despite the whole field being winter wheat.

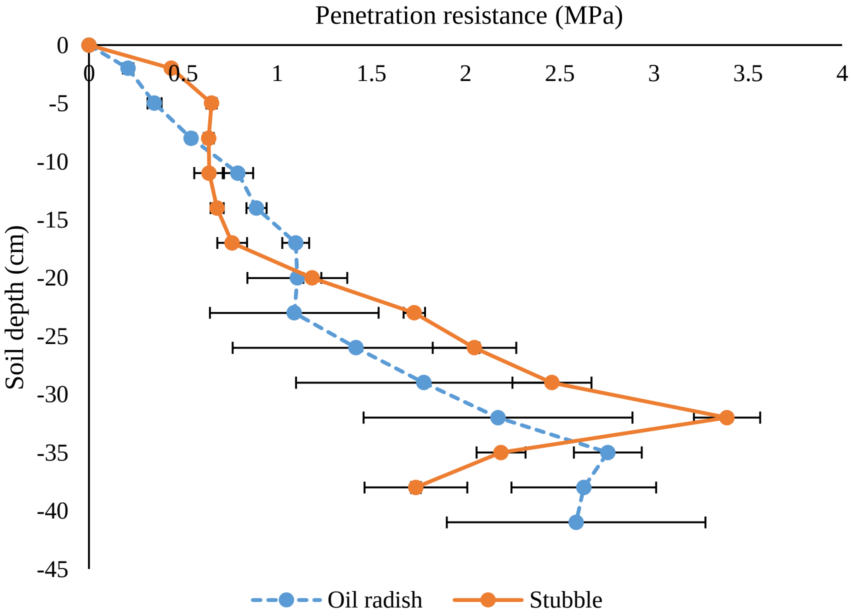


Figure 6.2 Penetration resistance of field site in November 2015 during cover crop growth. Error bars show standard error of means at each depth

6.3.1.2 Sugar beet growth

Shear strength of the sugar beet seedbed was significantly lower following the oil radish cover crop than following the over-wintered stubble (*P<0.001* Fig 6.3). Sugar beet after oil radish had a significantly greater plant population than sugar beet following stubble (*P=0.02* Fig 6.4). A population of 101,556 plants ha^{-1} and 91,556 plants ha^{-1} following the cover crop and stubble respectively. Sugar beet NDVI values were significantly greater following oil radish cover crop.

This difference was consistent throughout the growing season (*P<0.001* Fig 6.5). Sugar beet following oil radish had a significantly higher sugar yield than sugar beet following over-wintered stubble (*P<0.001* Fig 6.6).

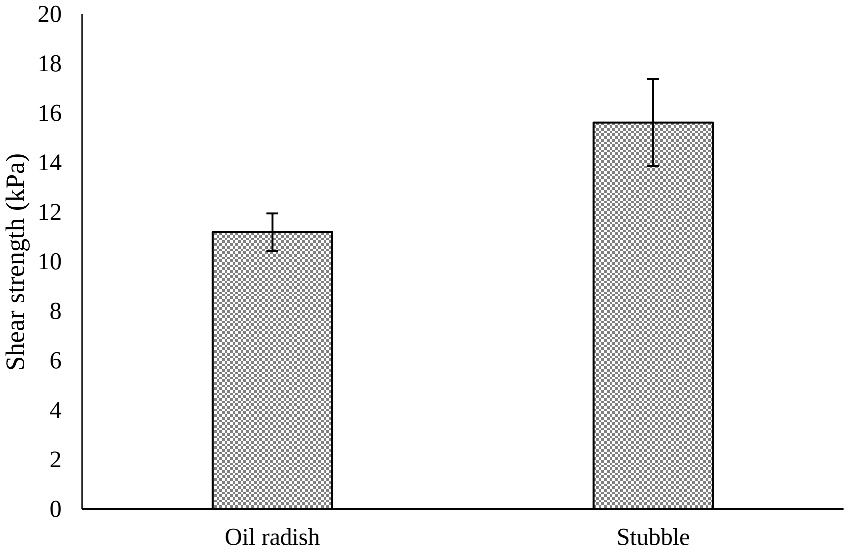


Figure 6.3 Shear strength of sugar beet seedbed. (*P<0.001*) error bars show standard error of means for each treatment.

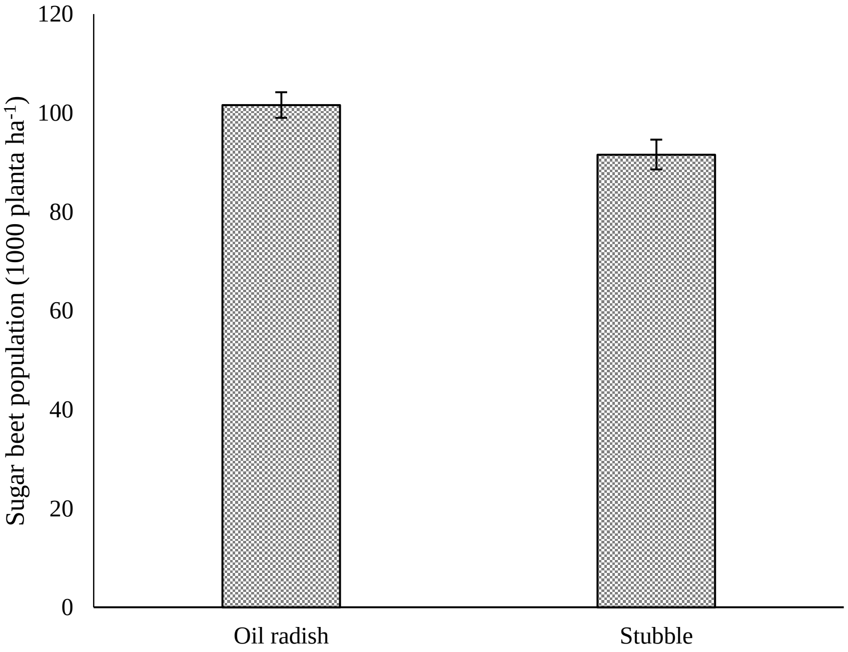


Figure 6.4 Sugar beet plant population (*P=0.02*) Error bars showing standard error of means of each treatment.

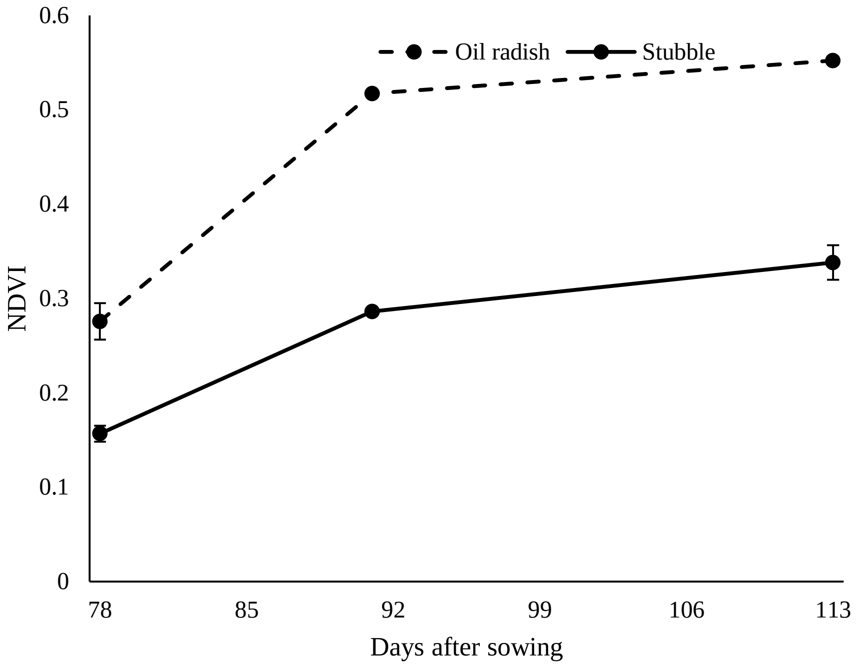


Figure 6.5 NDVI values for sugar beet over time following stubble or a cover crop. Error bars show standard error of means at each date. (*P<0.001*)

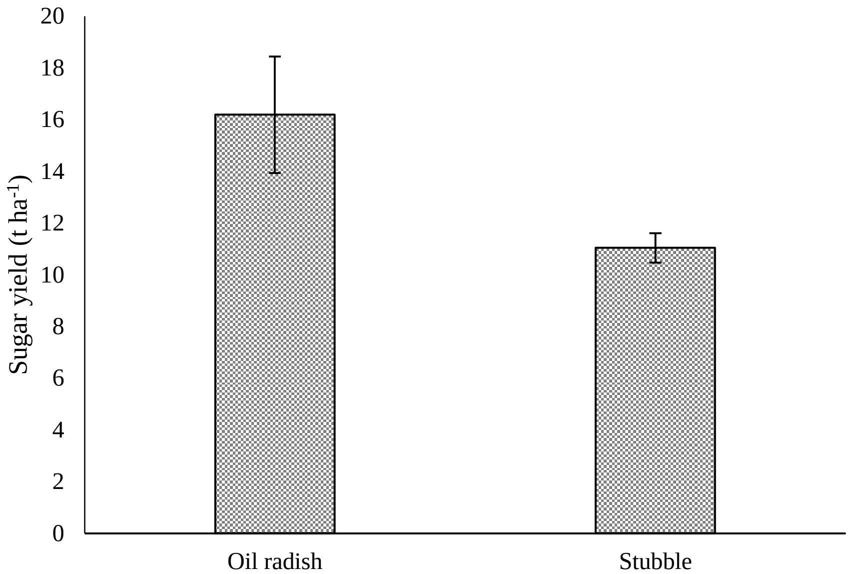


Figure 6.6 Sugar yield of treatments at harvest. (*P<0.001*) Error bars showing standard error of means

6.3.2 Holkham 2018-2019

6.3.2.1 Penetration resistance

No differences in soil penetration resistance were measured between the three treatments immediately prior to sugar beet drilling (Fig. 6.7).

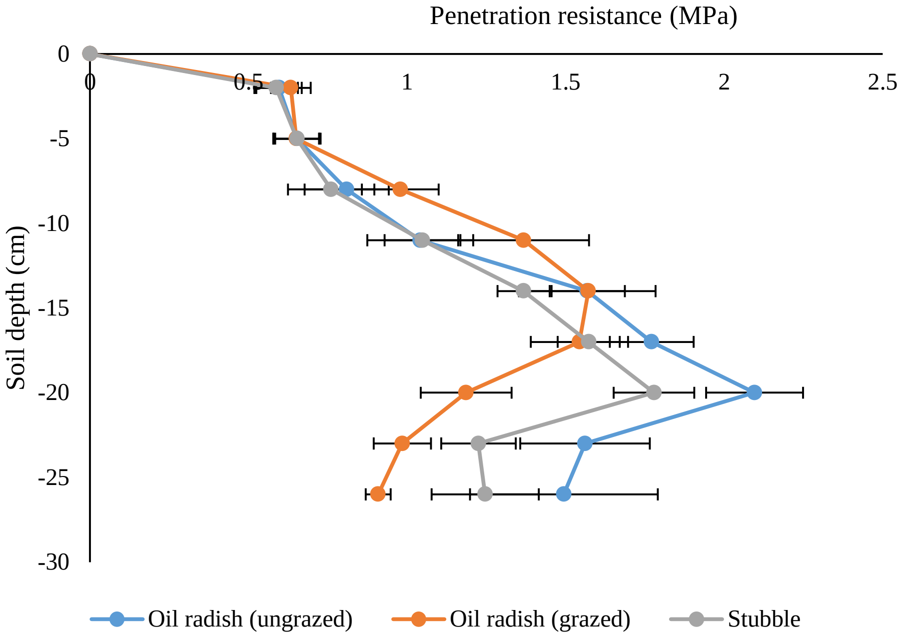


Figure 6.7 Penetration resistance of field trial area in May 2018 immediately prior to sugar beet drilling. Error bars show SED of means.

6.3.2.2 Shear strength

No differences in soil shear strength were recorded between field sub sections. Mean shear strength for the field site in 2018 was 8.6 kPa. There was also no difference in sugar beet plant population across the field and mean sugar beet population was 105,000 plants ha^{-1}.

6.3.2.3 Aggregate size distribution

No differences in soil aggregate size distribution were measured at any point of the 2017-2018 field trial (Fig 6.8) although there was a trend for more soil aggregates with a diameter of >10 mm in cover crops that were grazed.

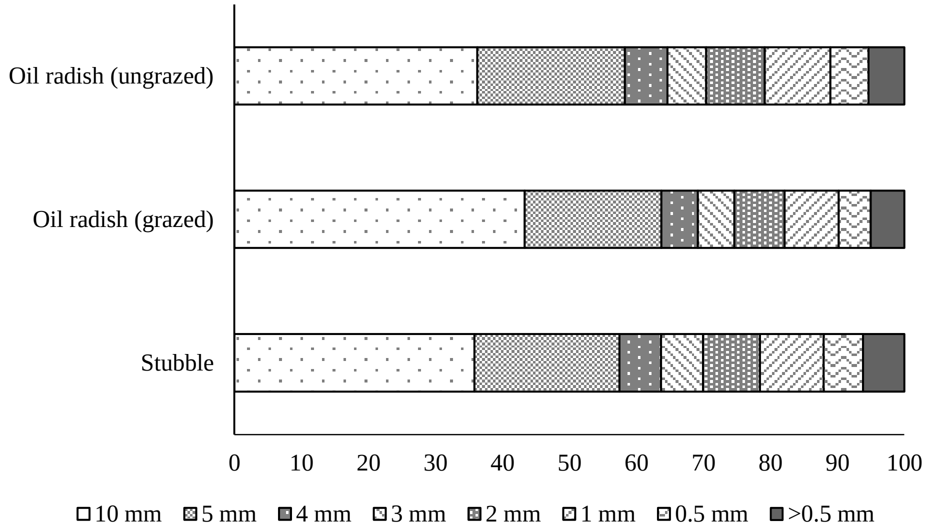


Figure 6.8 Aggregate size distribution of field site in March 2018 after cover crop destruction and before sugar beet drilling. No significant differences between treatments

6.3.2.4 Sugar beet canopy growth

Canopy cover was significantly larger for sugar beet following the oil radish cover crop between 60-100 DAS (*P<0.001*). However grazing did not have an effect and differences between treatments diminished through the summer (Fig.6.9).

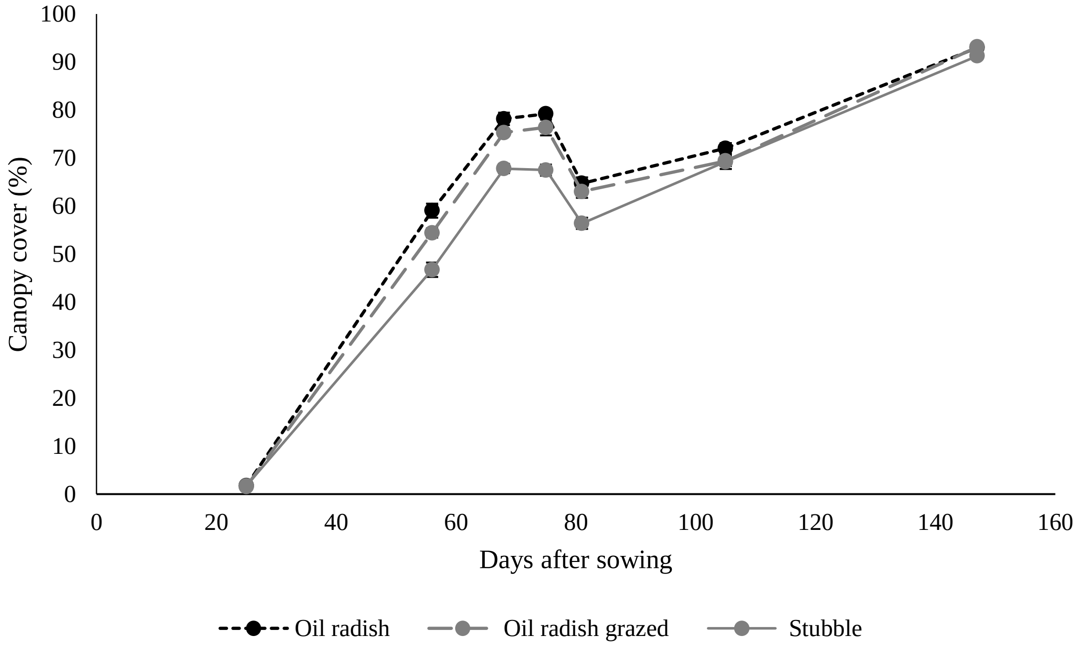


Figure 6.9 Canopy cover of Holkham field site over time 2018. Error bars show SEM for each treatment at each date. Significant differences between cover cropped (grazed &un-grazed) and stubble treatments on 56, 698, 75 & 81 DAS (*P<0.001*).

Sugar beet following the oil radish cover crop had significantly lower canopy temperature than sugar beet following stubble during the drought in June 2018 (*P=0.01* Fig.6.10). No differences in canopy temperature were measured between grazed and un-grazed cover crop treatments. Mean SPAD values for sugar beet following oil radish grazed and ungrazed were significantly greater than sugar beet following stubble (*P<0.001,* Fig. 6.11).

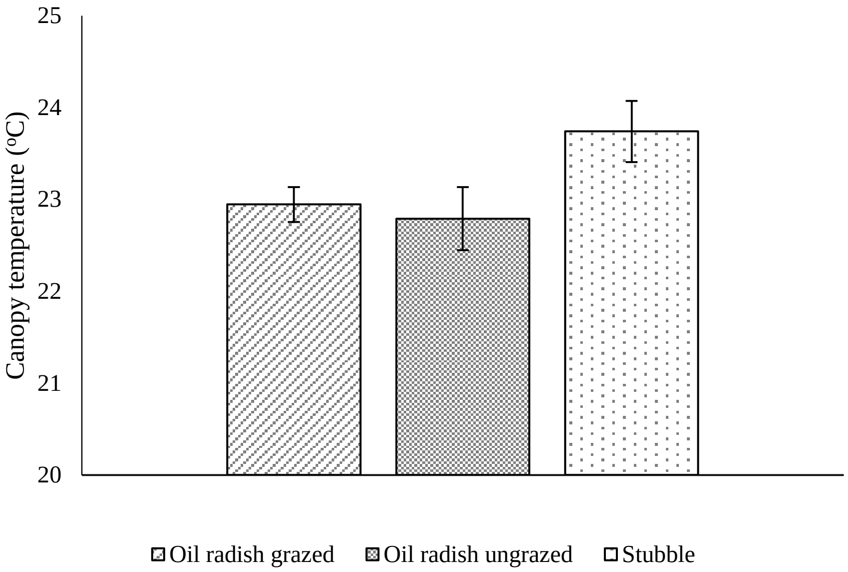


Figure 6.10 Sugar beet canopy temperature on June 28th 2018 at Holkham. Significant difference between cover crop and stubble treatment (*P=0.001*) Error bars show SEM of each treatment.

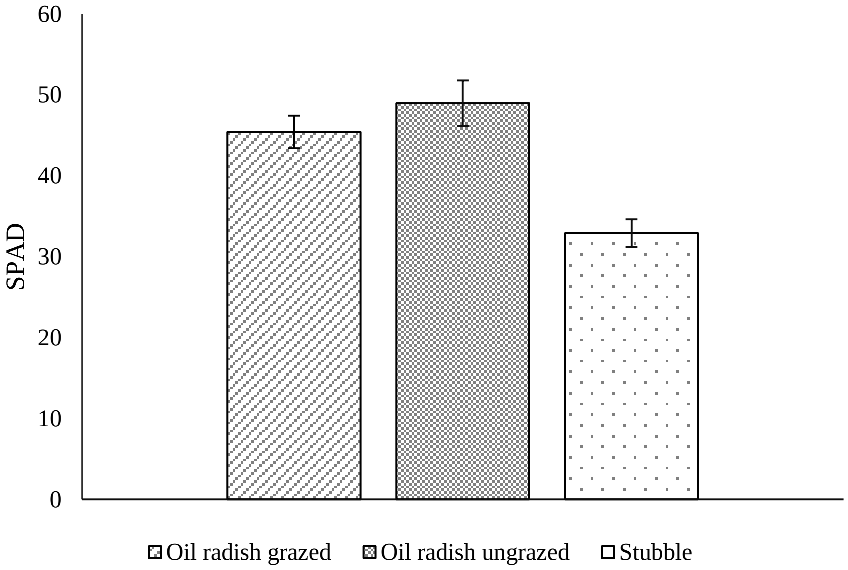


Figure 6.11 SPAD values of sugar beet 28th June 2018 at Holkham. No differences between oil radish grazed & ungrazed (*P<0.001*)

There were significant differences in nitrogen % in each plant (*P*<0.001 Fig 6.12). Nitrogen content of sugar beet leaves on the 28th June was significantly greater in sugar beet following oil radish (*P=0.001*, Fig 6.13). Sugar yield was significantly greater following the ungrazed oil radish cover crop than sugar beet after stubble (*P=0.046* Fig 6.14). There was no difference to sugar yield between grazed oil radish and the stubble treatment.

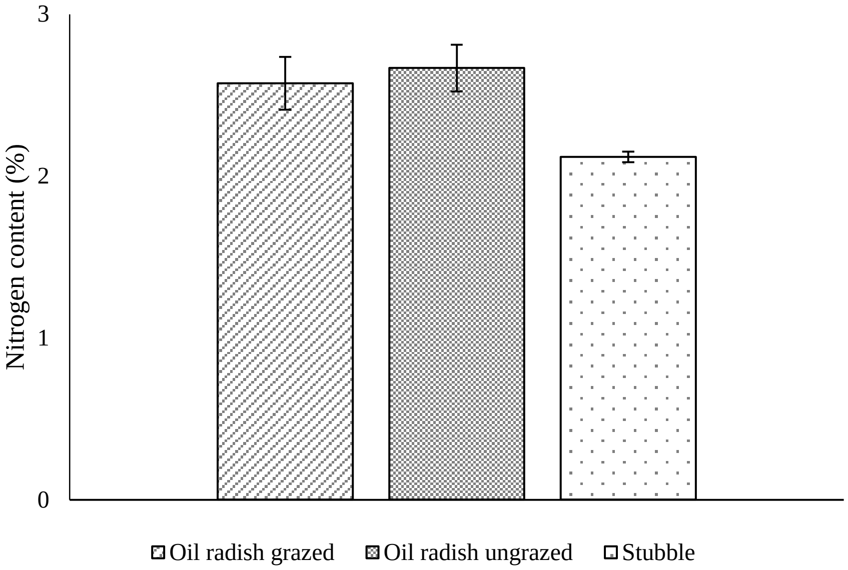


Figure 6.10 Mean nitrogen content per plant measured in June 2018. Error bars show SEM of each treatment. Significant difference between cover crop and stubble treatment (*P<0.001*)

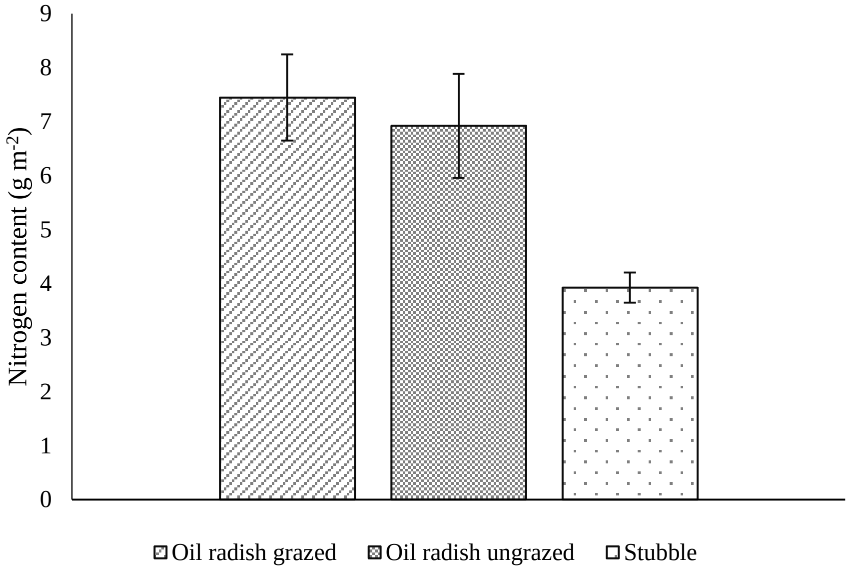


Figure 6.13 Nitrogen content per gram of leaf sampled in June 2018. Error bars show SEM of each treatment. Significant differences between cover crop and stubble treatment (*P=0.001*)

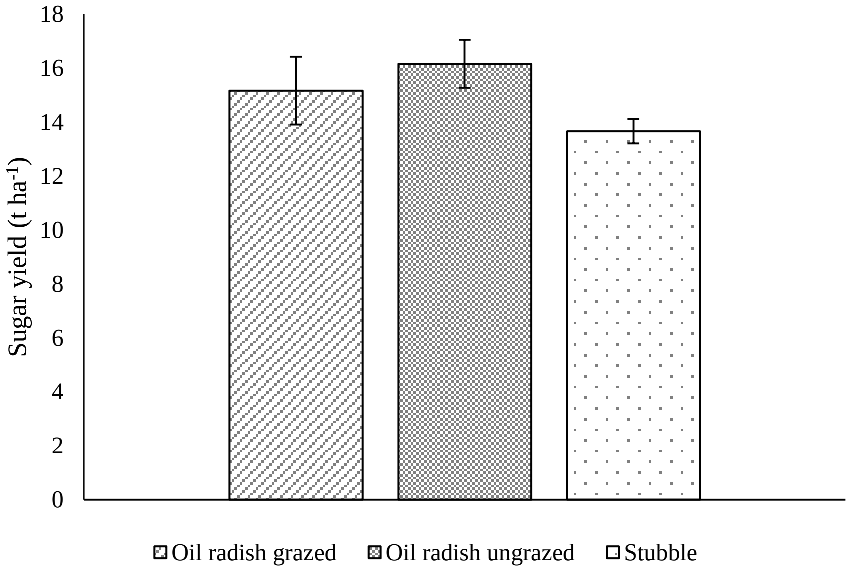


Figure 6.14 Sugar yield at harvest. No significant difference between oil radish treatments. Oil radish grazed did not produce a different sugar yield to beet following stubble. Sugar beet following ungrazed oil radish produced a significantly greater sugar yield than stubble (*P=0.046*). Error bars show SEM

6.3.2.5 X-ray Computed Tomography

No differences in soil porosity were measured between the oil radish grazed and ungrazed treatments and the samples were combined. Soil porosity was consistently greater post cover crop compared to soil post stubble. From 9-15cm depth there was a significant increase in porosity after the cover crop compared to stubble (Fig 6.15). Below 16cm depth the soil porosity was not different between treatments.

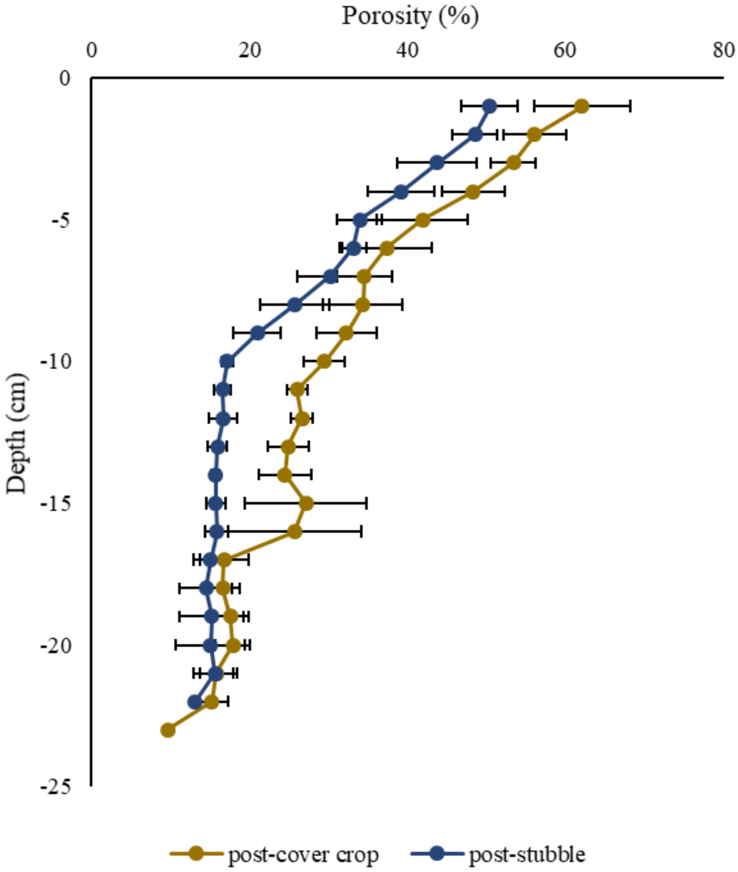


Figure 6.11 Soil porosity of soil treatments measured in October 2018. Significant differences measured between -9 and -16 cm. Error bars show SEM of each treatment at 1 cm increments. (*P<0.05*)

6.3.3 Shimpling field site

6.3.3.1 Penetration resistance

Autumn measurements of penetration resistance were not possible due to high soil moisture content at sampling. No differences in penetration resistance were measured at sugar beet drilling (Fig 6.16). Soil strength reached 1.5 MPa at approximately 20 cm depth and increased gradually with depth.

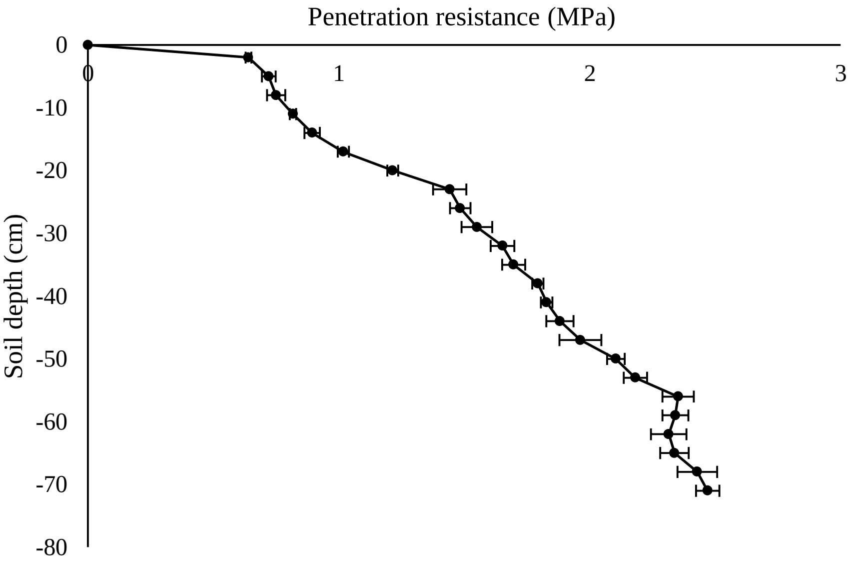


Figure 6.12 Mean penetration resistance of field experiment at sugar beet drilling

6.3.3.2 Soil aggregate size distribution

In January there was a significant reduction in aggregates with a diameter of more than >5mm relative to those 5mm diameter as a result of tillage radish, black oat and forage rye compared to bare soil (*P=0.035,* Fig.6.17). Egyptian clover was not significantly different to either bare soil or the other cover crop treatments (Fig 6.17). After seedbed preparation there were no differences in soil aggregation.

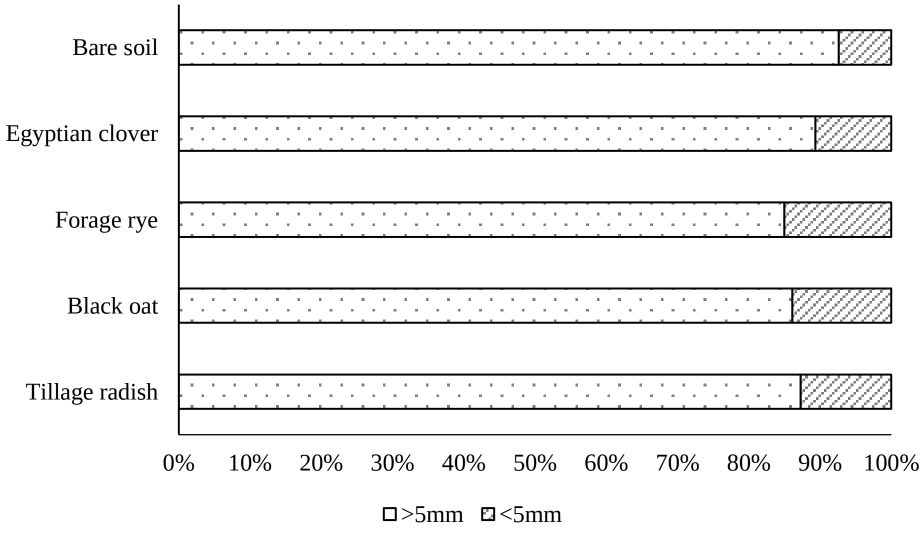


Figure 6.13 Aggregate size distribution of field trial in January 2018. Significant differences between treatments (*P=0.035*)

6.3.3.3 Cover crop biomass

Cover crops produced varying amounts of above ground biomass. Egyptian clover produced 10.68 g m^{-2}, tillage radish produced 58.29 g m^{-2} which was not significantly different to any treatment. Forage rye and black oat produced 65.35 g m^{-2} and 82.98 g m^{-2} which was significantly more than Egyptian clover (*P=0.009*).

6.3.3.4 Sugar beet seedbed and establishment

Seedbed soil moisture and bulk density were not significantly different between treatments with mean values of 21.4% moisture and 1.23 $g.cm^{-3}$ respectively. Establishment was not affected by the cover crop treatments and the mean establishment was 103,527 plants ha^{-1} giving an emergence rate of 82.6%. No differences in shear strength were measured between treatments ($P=0.142$). Mean shear strength of the sugar beet seedbed after rolling was 17.33 kPa.

6.3.3.5 Sugar beet canopy growth

Repeated measures analysis of variance showed no differences in sugar beet canopy cover were measured at 28 DAS (Fig 6.18). After 65 DAS beet following tillage radish had a larger canopy cover than all other treatments. At 70 DAS beet following forage rye had a significantly lower canopy cover than all other treatments ($P=0.002$, Fig.6.18). Egyptian clover and black oat treatments had a lower canopy cover than tillage radish but not bare soil which was not significantly different to tillage radish. At 77 DAS canopy cover after forage rye was significantly lower than bare soil and tillage radish but not black oat or Egyptian clover which were not significantly different to bare soil. At 108 DAS, sugar beet following bare soil and tillage radish were significantly larger than forage rye but not Egyptian clover or black oat which in turn were not significantly larger than forage rye. After 148 DAS sugar beet following bare soil were significantly larger than beet following forage rye. Egyptian clover, bare soil and black oat were not significantly different to either tillage radish or forage rye.

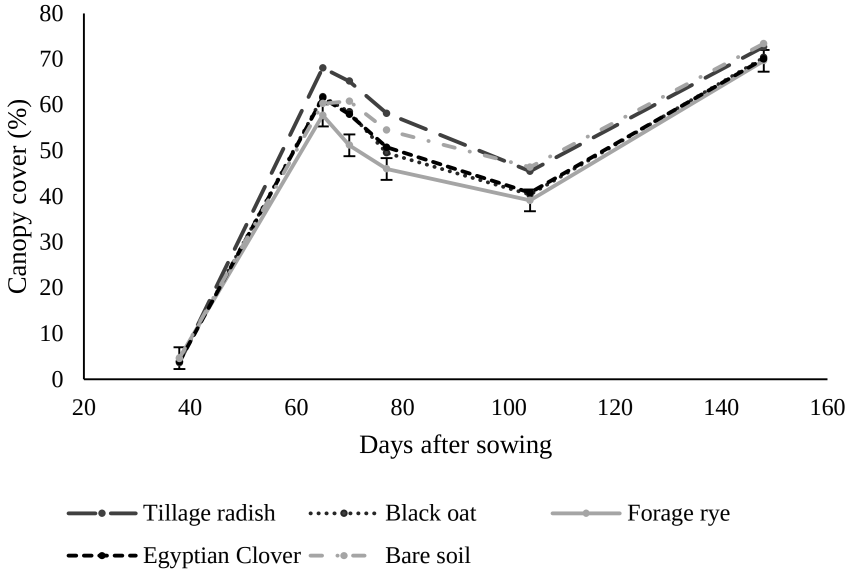


Figure 6.14 Sugar beet canopy cover over time at Shimpling field experiment. Error bars show SEM (*P=0.012*)

No significant differences in canopy temperature were recorded (*P=0.245*). Mean canopy temperature for 28 June 2018 was 28.9°C. Similarly, there were no SPAD value differences between treatments (*P=0.*131) at the same date and mean SPAD value was 39.90.

There were no differences in nitrogen % between cover crop treatments (Table 6.3). Tillage radish and bare soil produced significantly more sugar beet above ground biomass and nitrogen per unit area than Egyptian clover, black oat and forage rye.

Table 6.2. Nitrogen %, Sugar beet leaf biomass (g.m^{-2}) and total nitrogen content (g m^{-2}) of sugar beet at 77 DAS in 2018.

	Tillage radish	Forage rye	Black oat	Egyptian Clover	Bare soil	*P*	LSD
Nitrogen %	1.99	1.91	2.03	1.83	2.19	0.13	n/a
Leaf biomass (g m^{-2})	277.9	195.0	226.3	213.9	276.7	0.01	50.1
Total N content (g m^{-2})	5.57	3.37	4.61	3.89	6.07	0.01	1.369

6.3.3.6 Sugar beet yield

At harvest there was no significant difference between treatments in sugar yield however there was a trend for sugar beet following tillage radish to produce less sugar ha^{-1} (Fig 6.19). There was a significant negative relationship between sugar yield at harvest and canopy cover at 77 DAS (Fig 6.20).

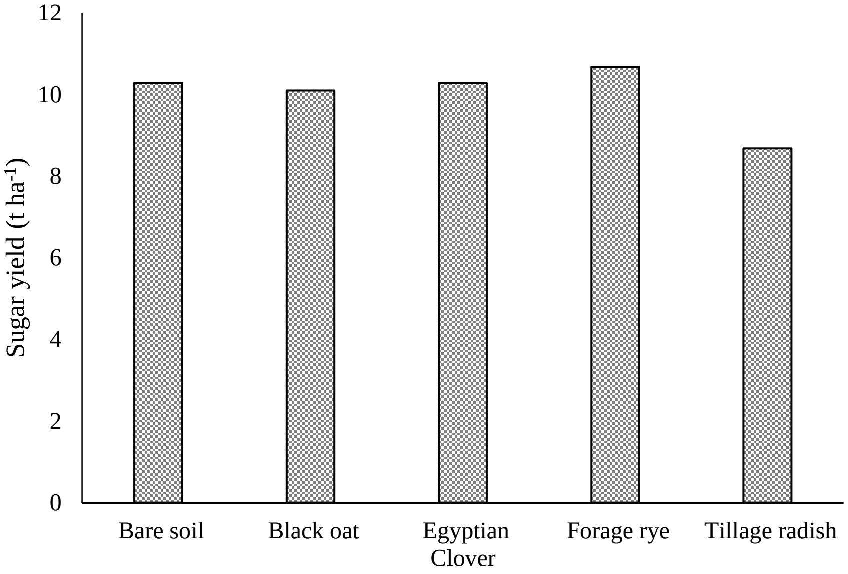


Figure 6.15 Sugar yield at harvest of experiment. No significant differences between treatments.

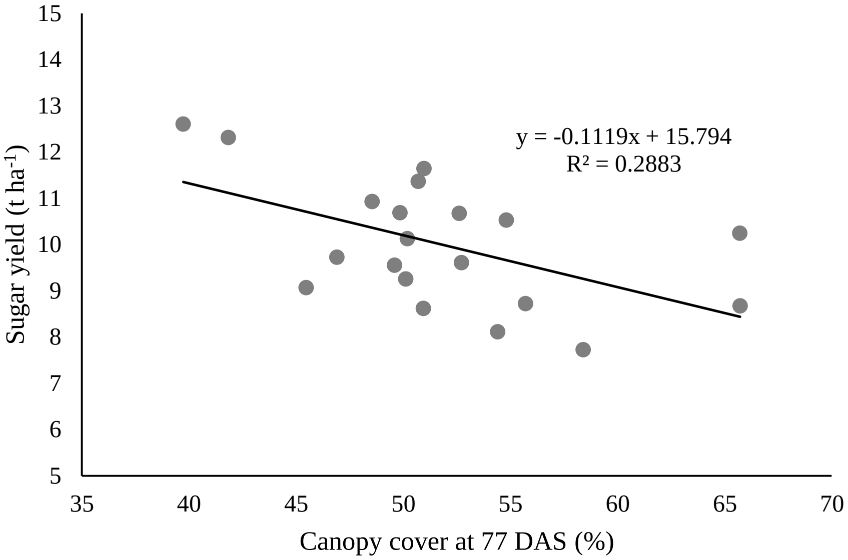


Figure 6.16 Significant negative relationship between canopy cover at 77DAS and sugar yield (*P=0.015*).

6.3.5 Weather Data

Weather data was collected from Met stations at South Creake, Norfolk and Brockley, Suffolk. During the heatwave of 2018, the field experiment at Shimpling experienced consistently higher air temperatures during the day time between 01/06/2018 – 01/08/2018 (Fig. 6.23). Using minimum and maximum daily temperatures and daily rainfall, accumulated thermal time and accumulated rainfall during the growing season of both cover crops and sugar beet were calculated for each year (Fig 6.24).

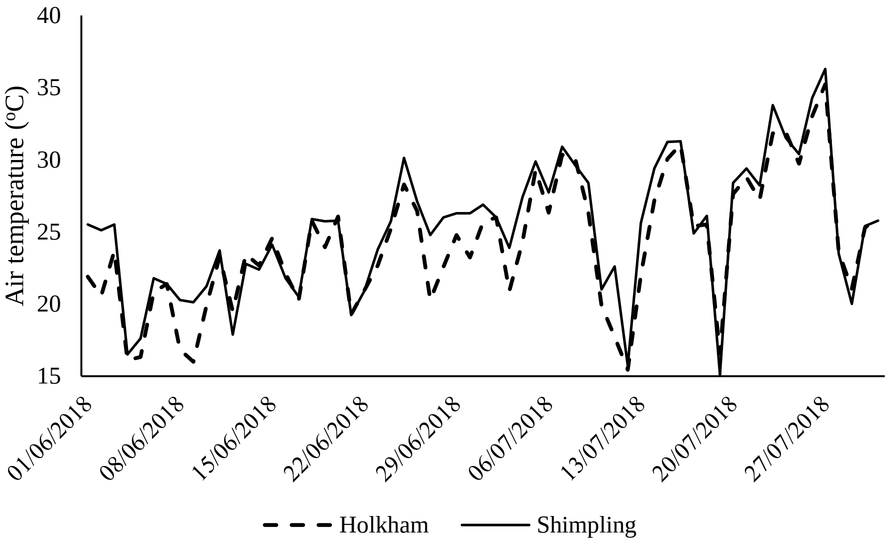


Figure 6.21 Daytime mean ait temperatures from Holkham and Shimpling field sites between June and August 2018.

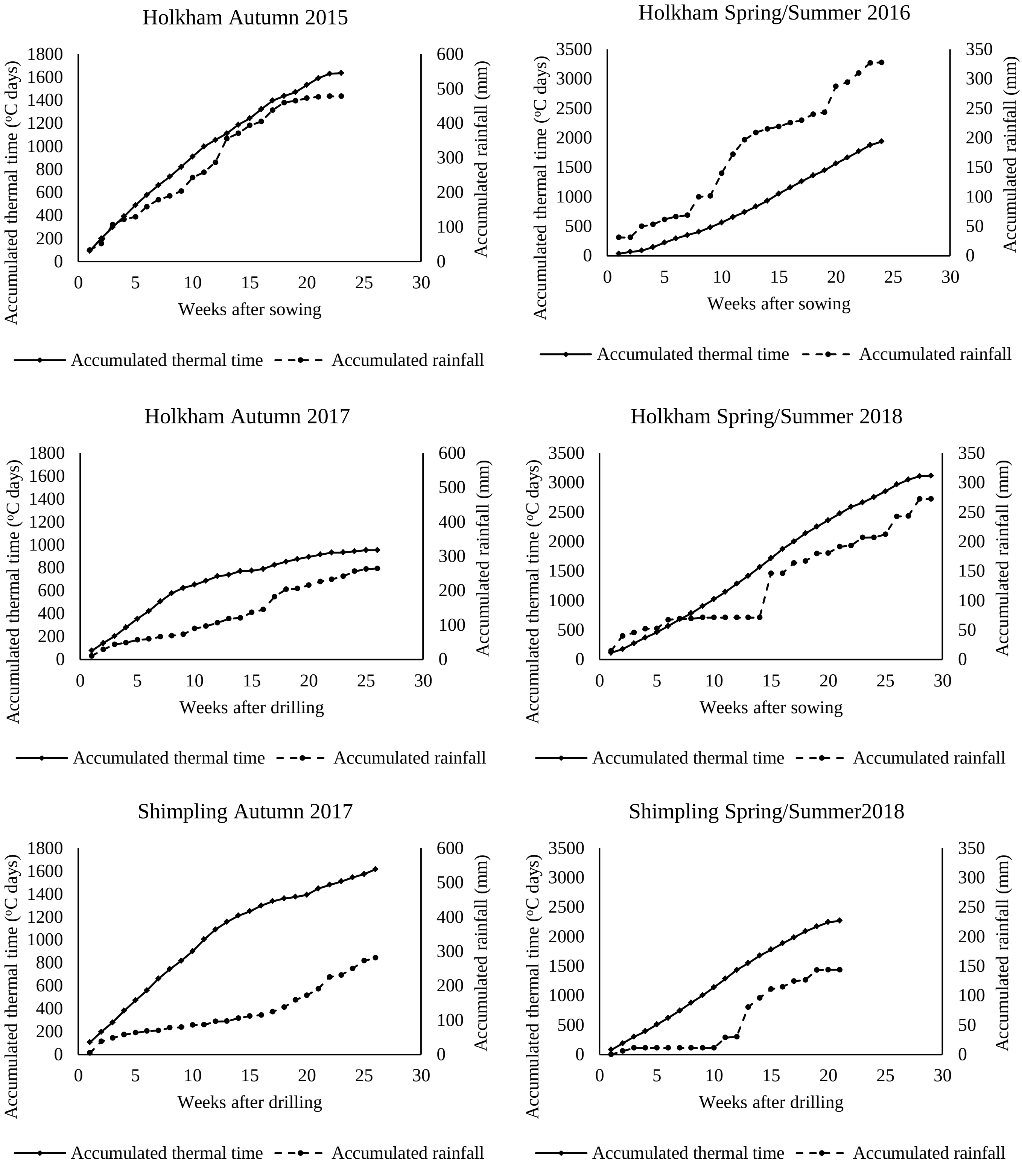


Figure 6.17 Accumulated rainfall and thermal time from field sites in each year. DAS starts when cover crops were drilled in autumn and sugar beet in spring

6.4 Discussion

6.4.1 The interaction between soil texture and the effects of cover crops on soil aggregation

The effects of cover crops on subsequent beet crops commercial farms varied, depending on the soil type. Differences in soil aggregation were measured on clay soils. This is likely to be as a result of the plasticity of clay soils which allows their structure to change shape in response to external force (Keller and Dexter, 2012). Changes to the aggregate structure of sand or loam soils is therefore more difficult and is likely to only occur where changes to the organic matter of the soil have taken place (Franzluebbers and Arshad, 1996). Changes to soil organic matter are only likely to take place over a number of years and therefore overwintered cover crops are unlikely to lead to changes in soil aggregation on sand and loam soils.

6.4.2 The effects of cover crops on soil strength

Differences between cover crop treatments in the strength of the soil surface were measured in both field sites. It is possible that this was a result of cover crop root growth and the interaction with soil moisture. Reductions in the soil surface penetration resistance and shear strength as a result of the cover crop are more likely the result of combined effects of cultivation techniques employed to establish the cover crop alongside cover crop root growth itself. When compared with stubble, which has not experienced any soil disturbance, cover crops resulted in a reduction in soil strength. It is likely that this would be beneficial to the growth of the following crop due to less restrictive soil conditions. Any reduction measured in soil penetration resistance only occurred at the Holkham field site and also diminished with increasing depth suggesting it unlikely that the cover crop growth had influenced the soil resistance during the autumn period. However, the penetration resistance did not reach the reported limit to sugar beet growth of 2.5 kPa until deeper in the soil layers (Fueki and Takeuchi, 2010), suggesting that penetration resistance should not have resulted in differences of sugar beet growth.

6.4.3 External factors affecting cover crop effects on different soil textures

The inclusion of grazing at Holkham did not appear to have any impact on soil structure. It is likely that this was as a result of the soil conditions at the point of grazing. Studies have suggested that there is only a significant risk of soil compaction when grazing occurs at high soil moisture and at stocking densities that are greater than recommended (Greenwood and McKenzie, 2001). Peng et al. (2004) found that coarse textured soils with lower water content are less at risk of compaction compared to fine textured clay soils. In addition, Clark et al. (2004) found that compaction from grazing was only present in the top 10cm of soil which is easily remediated by seedbed preparation resulting in no loss of yield. We confirmed this situation as soil porosity was not different as a result of grazing in the cover crop treatment. It is likely that the situation would have been different if grazing had been included on the clay soil at Shimpling as the greater soil moisture during the winter and the relatively greater compactibility of clay soil would have put the soil profile at much greater risk of soil compaction.

6.4.4 The effect of cover crops on sugar beet establishment and plant population

In most cases cover crop treatments did not influence sugar beet establishment. In the first season at Holkham there was a slight decrease in plant population following the stubble treatment which is likely to be as a result of the increased seedbed shear strength. However, the plant population following either treatment did not fall below the level that the crop is able to compensate for (Jaggard, 1979) . This suggests that in terms of the sugar beet plant population there was no effect on sugar beet yield potential. Sugar beet establishment has been linked directly to seed-soil contact in order to produce a sufficient plant population (Jaggard, 1979, Blunk et al., 2018). It is possible that if secondary tillage practices had not been carried out prior to sugar beet drilling on the heavy clay field site, the cereal cover crops may have had a relatively positive effect on sugar beet establishment as a result of their larger proportion of small aggregates. It is important to highlight the minimal effect that cover crop residues had on sugar beet establishment. Early destruction and removal of crop residues avoided negative impacts on crop establishment that has previously been measured by Morris et al. (2009).

6.4.5 The effect of cover crops on sugar beet canopy growth

At Holkham, sugar beet canopy growth was consistently greater following an oil radish cover crop in comparison to over-wintered stubble. At Shimpling, the sugar beet canopy growth was greater following tillage radishes and over-wintered bare soil than black oat, forage rye and Egyptian clover. The differences in sugar beet growth at Holkham are likely to be as a result of greater soil porosity following the cover crop. It is unclear whether the increased porosity was as a result of the cultivations associated with cover crop growth or a result of increased biopores from cover crop roots. However, the cultivations of the field at sugar beet drilling were consistent across the field site suggesting the residual differences in porosity were indeed as a result of biopores created by the cover crop roots. Jakobsen and Dexter (1988) previously suggested that the increase of biopores can significantly increase root growth and water uptake of the following crop. It is possible that the increase in porosity lead to lesser constraints to sugar beet root growth and water and nutrient uptake (Bengough et al., 2006, Brereton et al., 1986). Furthermore, the increased porosity of the topsoil may have had a greater water availability to the crop. This may have had heightened benefits during the period of hot weather during June-August 2018. This is further supported by the significantly lower canopy temperature of sugar beet following cover crops in 2018 and the greater SPAD values in the same period which suggests that water and nutrient availability allowed for continued transpiration during the heatwave leading to lower water stress (Sharratt et al., 1983).

6.4.6 The interaction between cover crops and grazing and their effects on sugar beet water and nutrient uptake

Previous studies have suggested that the inclusion of grazing into agricultural rotations will mean better nutrient availability to the following crop (Cicek et al., 2014). Despite the use of crop residues containing nutrients by the livestock for growth, it has been suggested that the deposition of manure will allow greater carbon and nitrogen to be available more rapidly to the following crop (Duncan et al., 2016). It is possible that this effect contributed to the increased sugar beet growth and yield at the Holkham field site. Duncan et al. (2016) showed that carbon to nitrogen ratio (C:N) was lower for livestock manure than crop residues allowing more rapid uptake by crops following their growth. It has been suggested that nitrate release from cover crop decomposition is not rapid enough for sugar beet canopy establishment

(Allison et al., 1998b). However the increased nitrogen availability from manure is more likely to contribute to expansion of the sugar beet canopy. Therefore the nitrogen availability following grazing may have contributed to canopy expansion in the first season at Holkham. The lack of differences in canopy growth after grazed and ungrazed cover crops in the second season at Holkham suggests that grazing did not contribute greatly however. Nevertheless, the maintained growth and yield of the sugar beet after grazing in addition to the financial reward for grazing the cover crop in favour of chemical destruction may be an added benefit to cover crop inclusion to the crop rotation.

6.4.7 Sugar beet growth on clay soil following cover crops

Sugar beet on the clay soil appeared to have larger, more efficient leaf canopies in response to bare soil and tillage radish and sugar beet canopy growth was relatively lower after forage rye, black oat and Egyptian clover. It is possible that rather than oil radish allowing better water and nitrogen availability, the other cover crop treatments may have had detrimental effects on sugar beet growth. Decomposition and release of captured nitrogen by cover crops is determined greatly by the carbon-nitrogen ratio (Wagger et al., 1998). It has been suggested that cover crops such as rye and clovers have a carbon:nitrogen that requires increased nitrogen, compared to brassicas, for the decomposition of the crop residues (Sievers and Cook, 2018). As a result nitrogen may become less available to the following crop (Wyland et al., 1995). Sugar beet has a high demand for available nitrogen during early growth to produce a leaf canopy capable to intercepting maximum PAR. As a result reduced nitrogen availability caused by decomposition of carbon-heavy crop residues is likely to have a detrimental effect on sugar beet growth. Sievers and Cook (2018) reported different decomposition rates of rye and hairy vetch which in turn influenced subsequent soil nitrogen availability. As a result it is possible to suggest that cover crops with a high C:N need to be destroyed with a longer delay before a spring crop is established compared to brassica species which typically have a lower C:N.

6.4.8 The relationship between sugar beet canopy growth and final crop yield

In most situations there was a strong relationship between sugar beet leaf growth and the root dry weight and final yield. At Holkham in 2018 the relationship between canopy growth and sugar yield was not possible to analyse differences in yield reflected the differences in canopy cover. It is possible that this is due to the crop producing the majority of the yield in the latter part of the season when canopy differences were less pronounced. However, it is also possible that if the difference between the two treatments was driven by water availability, the areas of the crop that were more water stressed partitioned a greater proportion of biomass to root production than leaf production.

Despite the large differences in canopy growth at Shimpling during the heatwave, there was little difference in sugar yield between treatments. It is possible that the yield for the treatments was not significantly different for two reasons. The greater leaf growth of sugar beet following bare soil and tillage radish prior to the onset of the drought and heatwave may mean that sugar beet were more susceptible to excess water loss which may have resulted in suboptimal transpiration of the crop due to their excessive canopy size leading to greater water loss (Hoffmann and Kenter, 2018).

The differing responses of sugar beet yield to larger canopy growth is likely to be as a result of the heat stress on the crops. At Holkham, near the coast, the field site experienced consistently 3°C lower daytime temperatures between June and August 2018 compared to Shimpling. Therefore it is likely that the sugar beet with larger crop canopy was able to effectively use the water supply and the PAR available to it whereas the sugar beet with larger canopy at Shimpling will have experienced greater heat stress and lower water use efficiency. Similarly, Blum (2009) suggested that when temperatures are high, water is lost through non-stomatal transpiration which equates to water loss without photosynthetic gain.

When water and nutrient deficiency are not present and pest and disease pressure is excluded crop growth is limited by intercepted radiation and genetic potential (Hoffmann and Kenter, 2018). This suggests that the differences in sugar beet growth are as a result of better access to water and nitrogen. It is important to highlight that one season measured had extreme heat and drought conditions during the early summer. It is therefore not possible to say that the differences in sugar beet growth that were observed will be consistent every year or whether they will only be evident in years when environmental stress is sufficient.

6.4.9 Long term inclusion of cover crops into the crop rotation

It has been suggested that the inclusion of cover crops into long term management of the crop rotation can increase the organic matter content of the soil. There is some debate whether this may or may not allow better water availability to crops (Minasny and McBratney, 2018). However, if rooting of the following crop is achieved, as we have seen here, there is a chance that water availability can be increased.

6.5 Conclusions

The inclusion of an autumn sown cover crop on a loamy sand resulted in greater soil porosity, increased water and nitrogen uptake and enhanced sugar beet growth and yield. This shows that cover crops can increase the water availability to the following crop, confirming sub-hypothesis 3.

Grazing of cover crops at Holkham, on loamy sand, did not result in soil compaction and offered the opportunity to harness financial benefit from grazing and may have contributed to better nutrient availability to the following crop. However, this will be dependent on the intensity and timing of grazing.

On clay soil sugar beet growth appeared to be retarded after forage rye, black oat and Egyptian clover, possibly due to a negative effect on nutrient availability and growth of the subsequent sugar beet crop in the early season. This suggests that there may be some characteristics of cover crops that are favourable to some environmental conditions as set out in sub-hypotheses 1. However, it is difficult to say whether the interaction was with soil texture or other environmental conditions during their growth.

The differences experienced on different sites and between each year showed that the air temperature and water availability are likely to have an effect on cover crop growth. It is difficult to quantify the effect at these sites during cover crop growth however EMI, thermal imagery and SPAD showed that temperature and water availability were effected by cover crop growth prior to sugar beet.

Where sugar beet were cultivated in extremely high temperatures there was a negative effect of a large canopy which appeared to lead to excess water use and lower sugar yield.

Chapter 7: General discussion

7.1 Introduction

The aim of the project was to understand and quantify the effects of cover crops on soil physical properties and the growth and yield of subsequent sugar beet crops. The hypothesis was that cover crops improve soil structure which results in improved sugar beet growth and yield. The project was conducted using a number of different scales, including controlled environment experiments, replicated field experiments and large scale field experiments on commercial sugar beet farms. The aim was to understand the potential of cover crop growth and their effects on soil structure, by utilising controlled environment experiments and follow this with field scale experiments on a range of soil textures to understand how cover crops interact with other environmental factors. Data was collected over a number of years and experiments and has been analysed and discussed accordingly.

7.2 Identifying the effects of cover crops on soil aggregation

Cover crops had the ability to influence soil aggregation during their growth. However, this was dependent on a number of factors. Findings from glasshouse experiments suggested that the effect of cover crop growth on soil aggregation was dependent on root density and may interact with soil moisture. In glasshouse experiments, the effects of cover crops on soil aggregation appeared to be more pronounced when the volume of soil was smaller suggesting the effects are related to root length density. Furthermore, when soil moisture was lower, cover crops produced a greater proportion of small aggregates. It is likely that cover crops with greater root density throughout the soil profile will directly affect the distribution of aggregates at the same time as causing a wetting and drying effect on the soil profile.

It is well established that ‘wetting/drying’ cycles in the soil profile have a considerable effect on the production of smaller aggregates (Utomo and Dexter, 1981, Misra et al., 1986, McKenzie and Dexter, 1988, Ruiz et al., 2015). The wetting and drying cycles of a soil are driven by water uptake by plants. Thus we can assume that cover crops that have larger root systems coupled with the greatest water demand are likely to cause that greatest wetting/drying effect on the soil profile. Similar findings have been seen by Bodner et al. (2008). It is important to consider that in field conditions in temperate regions, low temperatures during the autumn and winter may reduce the ability of cover crops to take up water (Laine et al., 1993).

In field conditions there was less of an effect of cover crops on soil aggregation than previously seen in controlled experiments. The cause of this is likely to be a result of three factors. Initially, cover crop root length density in the field is likely to be lower than in controlled conditions as a result of the larger soil volume available for root elongation. As a result, the direct effects of roots on a volume of soil will be less.

The effects of wetting and drying cycles are likely to diminish during the autumn and winter as a result of cooler temperatures, leading to lower transpiration alongside increased rainfall and therefore less opportunity for the soil to completely dry out. This will be further affected by the cover crop species. Laine et al. (1993) showed that in field conditions, cereal cover crops cease transpiration earlier in the winter compared to brassica species which suggests that brassicas, in the winter, are more likely to lead to more pronounced wetting and drying cycles than other cover crop species.

Finally, the aggregation of field soil varies greatly depending mostly on clay content and organic matter content. Soil with higher clay content has greater plasticity and therefore is more likely to maintain changes to the aggregation or porosity than a soil with a greater proportion of sand (Keller and Dexter, 2012). It is possible that this is the reason that at Shimpling, on the clay soil, cereal cover crops produced a greater proportion of smaller aggregates whereas this effect was not seen at Sutton Bonington or Holkham where the soil had a smaller proportion of clay.

7.3 Understanding cover crop growth in field and controlled conditions

In field conditions it is established that the success of cover crop growth, as with many crops, is dependent on moisture availability and accumulated thermal time (Allison et al., 1998a). Allison et al. (1998a) also concluded that early growth of cereal cover crops is more dependent on thermal time accumulated whereas brassica cover crops were more dependent on available soil moisture. We found that, in controlled environment experiments and field experiments at Sutton Bonington, brassica cover crop species tended to produce the greatest quantity of biomass with cereal cover crops producing more than legumes. At Shimpling however, we found that cereal cover crops produced more above ground biomass than both brassicas and legumes. It is possible that, as found by Allison et al. (1998a), the conditions immediately after drilling were more favourable to cereal growth than brassica growth and it is more likely to be as a result of weather and moisture conditions rather than the soil texture.

Many of the commercially available cover crops are marketed in combinations of numerous species. It is often suggested, by seed producers, that the combination of cover crop species will result in a hybridised effect of two or more species root characteristics. In some circumstances, particularly where rye (*Secale cereale*) is used, controlled environment studies have shown that there may be negative implications of combining cover crop species as a result of interspecies competition responses such as allelopathy (Dhima et al., 2006). However, field experiments have suggested that there is no substantial allelopathic effect of rye on the growth of other cover crop species but cover crops may prevent growth of other species due to their vigorous growth and shading effect (Lawley et al., 2012). Findings from this project concluded that there was no negative effect of combining species on above ground biomass production or overall root growth which is in agreement with previous studies.

In contrast to a negative effect of combining cover crop species, it has been suggested that the combination of species can lead to better plant and crop growth as has been seen when utilising techniques such as intercropping. Hallam et al. (2001) found that combining forage species can lead to an increase in above ground biomass production. We did not see this response in either controlled environment experiments or field experiments which may appear unusual. However, Liu et al. (2018) has shown that increases in yields of intercropped fields, compared to monocrop fields are greatest when using row crops with optimum spacing. Therefore, it is possible that cover crops may not benefit from being combined unless sown as row crops which may be a consideration for further development of cover cropping techniques.

The combination of cover crop species has also been linked to increasing plant biodiversity of an ecosystem. It is widely accepted that an increase in plant biodiversity will have benefits to biodiversity of fauna (Bonkowski et al., 2009). However, there have been suggestions that during autumn conditions monocrops are likely to produce more above ground biomass than combinations and there is insufficient time for the biodiversity of the cover crop to have a meaningful effect on soil fauna (Bonkowski et al., 2009, Malezieux et al., 2009).

We found a strong relationship between above ground biomass production and root growth in controlled conditions and in field conditions. This suggested that above ground biomass production is a good indicator of cover crop root growth. We also found, cover crop species produced the same distribution of root diameters, with the exception of tillage radish which produced significantly more roots with a diameter of > 4.5 mm. Despite tillage radish producing significantly more thick roots that all other treatments, roots with a diameter of >4.5 mm accounted for a very minimal proportion of the total root length density. This suggests that the aim of a cover crop should be to maximise total plant growth to maximise the effect on the soil profile. It also shows that there was no benefit to growing a combination cover crop compared to a monoculture cover crop. Therefore, finding a cover crop that suits the autumn conditions to maximise growth is the priority rather than increasing cover crop biodiversity.

It is important for cover crop users to consider the effects of maximising their growth on the following crop. There is the potential for above ground biomass to have negative effects on the following crop. Excess crop residues have been shown to reduce sugar beet establishment and yield if not properly incorporated into the soil (Morris et al., 2009, Richard et al., 1995, Janzen and Radder, 1989). Furthermore it has been shown that cereal cover crop residues are particularly at risk of resulting in poor growth of the following sugar beet crop (Gauer et al., 1982). Therefore, it is likely that growers will have to consider destruction method alongside maximal cover crop growth when making decisions about the inclusion of cover crops. This will be highly dependent on weather conditions during the growing period as winter weather often reduces the window for tillage and chemical destruction of cover crops. As a result, destruction method and timing is an area for greater research.

7.4 Understanding the impact of cover crops on soil structure and growth of the subsequent sugar beet crop

7.4.1 Effect of cover crops on soil conditions during autumn

Across the experimental sites and scales the effects of cover crops on soil structure as a whole was varied. The effect of cover crops on soil moisture, throughout the soil profile was significant, particularly when autumn rainfall was not excessive. The drying effect of cover crop growth on the soil profile could have a number of implications. The moisture content of the soil governs the point at which tillage should take place (Dexter and Bird, 2001). High soil moisture during the autumn and winter can delay tillage which is necessary to prepare the seedbed for the following crop. Depending on rainfall, the inclusion of a cover crop may be able to reduce soil moisture to the optimum tillage range. However, it is possible that cover crop growth could dry the soil too much making tillage impossible until further rainfall. The drying effect of cover crops has also been highlighted as a possible problem for the recharge of groundwater and aquifers, which may have negative implications for water availability to the following crop and poorer crop growth (Allison et al., 1998b, Gauer et al., 1982). We did not see negative implications of this cover crop drying effect on the soil profile in any of the experiments conducted. This is likely to be a result of destruction timing of the cover crops, in field experiments, giving a sufficient time period for the soil profile to reach field capacity.

The effects of cover crops on earthworm populations, at Sutton Bonington was significant. In agreement with Crotty and Stoate (2019) it is likely that this is as a result of a food source being present during the autumn and winter compared to the treatments not containing a cover crop. Unlike Crotty and Stoate (2019) we did not observe that brassica cover crops result in greater earthworm abundance and instead found that earthworm population responded to the presence of a food source and soil moisture.

Earthworm abundance is often considered an indicator for soil health. Furthermore, their activity, alongside root growth, has been linked to the production of biopores through the soil profile (Blackwell et al., 1990, Han et al., 2015). Thus, the combined effect of root growth and earthworm activity may result in better movement of air and water through the soil profile and aid the uptake of water and solutes by subsequent crops (Gish and Jury, 1983). This idea should be treated with caution as Stroud et al. (2017) has suggested, deep burrowing earthworms that contribute most to the production of soil biopores, are unlikely to be affected by a single year of cover crops. Therefore, our findings may not be sufficient evidence to suggest that the increase of earthworms will have a meaningful effect on the long term porosity of the soil. As a result it is difficult to conclude the direct effects of earthworm activity on root growth and solute uptake of the subsequent crop, which is determined in part by soil porosity.

It is likely that this is as a result of environmental factors having a greater effect than cover crop growth. It has been established that, on soils with a high sand content, earthworm activity is hindered, particularly when soil moisture is low (Lee, 1985). Lee (1985) also showed that in soils with a high clay content, which are at risk of water logging, high soil moisture can lead to anaerobic conditions which have a negative effect on earthworm activity. Earthworm abundance has been shown to be negatively affected by intense soil disturbance such as inversion tillage and the harvest of root crops (Crittenden et al., 2014). Thus it is difficult to predict how long the positive effect of cover crops will last in conventional tillage systems particularly when they are followed by a sugar beet crop.

7.4.2 Effect of cover crops on early growth of sugar beet

Overall, the effects of cover crops on sugar beet establishment were minimal. At Sutton Bonington and Shimpling establishment was not affected by cover crops. The lower sugar beet population in 2018 is likely to be as a result of the dry weather conditions during the spring. The lack of differences seen as a result of cover crop treatments can be attributed to the seedbed shear strength, bulk density and soil moisture which were similar, on the whole, between treatments. At Holkham, in the first season we saw a slight reduction in plant population following overwintered stubble which is likely a result of higher shear strength. However, it is important to point out that even in the stubble treatment, plant population was not limiting according to previous studies (Jaggard, 1979).

In controlled conditions we found that radish roots did not properly decompose. This appeared to restrict sugar beet storage root growth which had a negative effect on overall plant yield, due to excess compression of the topsoil. However, it is unlikely that this level of compression of the soil would occur in the field. The cool temperatures and of the winter and freeze-thaw action would likely to lead to more rapid decomposition. Furthermore, in field conditions the combination of a larger soil volume and tillage should reduce the risk of lateral soil compression as a result of cover crop roots. It is, however, possible that had radish roots decomposed fully in the soil, that the number of soil biopores may have increased resulting in greater soil porosity (Li and Ghodrati, 1994).

The effect of crop residues were not specifically tested during the experiment. Given the differences in above ground biomass between treatments and the absence of differences in plant population, we can assume that cover crop residues did not significantly impact on sugar beet population. This has been suggested as a potential problem with cover crop residues which have been shown to interfere with sugar beet establishment (Sievers and Cook, 2018, Morris et al., 2009).

Cover crop residues have also been linked to poor seedling growth as a result of interacting with nitrogen supply. It has been found that cover crops with a high C:N, such as rye, require a longer period of decomposition than species with a low C:N such as radish (Sievers and Cook, 2018, Wagger et al., 1998). If incomplete decomposition of high C:N cover crop residues occurs, denitrification of the soil can result, leading to deficiency of the sugar beet crop. We did not see any symptoms of nitrogen deficiency which suggests that cover crops were destroyed with sufficient time for denitrification to be avoided. Duncan et al. (2016) found that grazing cover crops by livestock can avoid denitrification as residues are broken down initially by the digestion process. While there are often concerns that grazing can increase soil compaction, short term grazing on soils with a high sand content should not have a negative impact (Greenwood and McKenzie, 2001)

7.4.3 Effects of cover crops on sugar beet canopy growth and yield

At Holkham sugar beet had better access to water following a cover crop. This is of particular importance as drought is the most important limitation to UK sugar beet yield (Jaggard et al., 1998). It is likely that this was a result of increased soil porosity caused by cover crop root channels. The increased porosity would also have avoided excess physical stress on the root, particularly when soil strength is high (Fueki and Takeuchi, 2010). This in turn is likely to have allowed sugar beet following the cover crop to maintain access to soil moisture for a longer period during the drought conditions, as suggested by the lower canopy temperature. As a result, the sugar beet were able to continue to transpire during the period of the year with the highest radiation receipts which is likely to have had a direct effect on sugar beet yield.

Unlike Holkham, at Sutton Bonington, the effect of the cover crops on sugar beet growth and yield were limited. Despite measuring differences in soil conductivity during cover crop growth, differences were minimal during sugar beet growth. This suggests that there was no benefit in terms of water availability to the sugar beet of cover crop growth. Furthermore, the lack of differences in penetration resistance suggests that there was no potential benefit to sugar beet access to the water supply, as a result of less limiting conditions. This suggests that the effects of cover crop roots, on porosity, either were minimal or not long lasting to the sugar beet crop. In 2017 it is likely that the lack of differences were in part a result of near perfect weather conditions when water was not limiting. Growth and yield were lower in 2018 compared with 2017 but there were no differences as a result of the cover crops.

The importance of avoiding soil constraints was highlighted in 2018. During drought conditions when soil strength increased, there was significantly higher incidence of root fanging following cover crops and bare soil compared to ploughed soil. The relationship between soil strength and sugar beet root fanging has been demonstrated by Koch et al. (2009), Lipiec et al. (2003) who found that with increasing soil strength and compaction, the risk of sugar beet root fanging increased. This highlights the requirement of sugar beet for non-restrictive soil conditions. Fanging of sugar beet roots is a problem for a number of reasons. Firstly, the terminus of a storage root is brittle and at risk of damage during harvest which can lead to a loss of yield for the grower (Hoffmann and Schnepel, 2016). Secondly, where a root has multiple termini, there is the risk of soil adhering leading to its removal from the field. This is both a problem economically as it can lead to financial penalties for the grower; and it is also an environmental issue as it may contribute to soil degradation.

While the sugar beet that followed ploughing had a lower incidence of root fanging, there is an appetite, from environmentalists, to see reduced cultivations of the soil. This is due to the suggested increase in carbon emissions that occur when inversion tillage is used (Willems et al., 2011). Studies have suggested that long-term soil management should focus on reducing tillage by using minimum-tillage, strip tillage and zero-tillage techniques, similar to those employed in conservation agriculture systems (Palm et al., 2014). Short term experiments have suggested that there is a yield penalty for sugar beet grown in this system (Laufer and Koch, 2017) however the long-term effects of moving to a conservation agriculture system for sugar beet production are not known. It has been suggested that after a number of years of non-plough based systems soil restrictions will be reduced by the production of biopores by plant roots and increased earthworm activity (Blackwell et al., 1990, Kautz, 2015). However, this may prove difficult for arable rotations containing root crops due to the unavoidable procedures of harvesting root crops in the autumn when soil tends to be vulnerable to compaction. As a result it is unlikely that a reduced tillage system is wholly suited to sugar beet crop rotations.

At Shimpling, the effect of cover crops and the extreme weather conditions resulted in unexpected effects on sugar beet growth. Following bare soil and tillage radish, the sugar beet had a significantly larger canopy but did not result in higher yield. It has been suggested that in periods of extreme heat, sugar beet leaves can lose excess water without transpiration contributing to sugar yield. It is possible that the larger canopy resulted in greater water stress during the hot, dry conditions which was not able to be recouped when the extreme conditions had finished. This phenomenon has been seen previously by Hoffmann and Kenter (2018) who also suggested that we may see this effect more commonly with increasingly extreme weather patterns. The complimentary glasshouse experiment showed that although nitrogen and cover crop growth had a slight but significant effect on subsequent sugar beet growth. However, the effects of water supply on sugar beet growth was greater than both nitrogen and cover crop growth. This suggested, as previously seen, water supply is the main limitation to sugar beet yield due to its role in photosynthesis and the conversion of atmospheric carbon to biomass (Jaggard et al., 1998, Werker et al., 1999).

7.5 Implications of findings

7.5.1 Implications for farmers

We have seen that cover crops can improve both soil structure and sugar beet growth and yield. This effect, however, is dependent on environmental factors such as soil texture and weather conditions. It is likely that inclusion of cover crops on sandy soils will be easiest to manage due to their free draining nature. We have seen that in these conditions cover crops can lead to increased soil porosity and improvements to sugar beet growth. Introducing cover crops to soils with higher clay content is likely to be more difficult to manage subsequent cultivation, due to the water holding capacity of the soils but as seen in controlled and field experiments, there is the potential for cover crops to increase the proportion of small aggregates in the soil profile which may allow better seedling establishment and removal of soil constraints. These findings are likely to be of particular use to growers who use cover crops as a means of providing environmental focus areas (EFAs) for subsidy requirements. Cover crop root growth is directly related to above ground biomass production and therefore decisions on species, combinations and destruction timing should be easier for farmers.

The effects of cover crops on water availability to the crop suggests that cover crops can improve growth of the sugar beet canopy but in years of extreme heat this can be detrimental to overall sugar beet yield. However, extreme weather conditions such as 2018 are difficult to predict and previous studies have suggested that the long term inclusion of reduced tillage, cover crops and conservation agriculture may improve water and nutrient availability to crops. This may be particularly pertinent in future years as extreme weather events are predicted to occur more frequently which may result in overall sugar beet yield potential decreasing (Collins et al., 2014, Hoffmann and Kenter, 2018). Furthermore, if farmers intend to use cover cropping as a method of reducing nitrate leaching or for prevention of soil erosion, this is possible without having negative impacts on sugar beet yield.

It is important to point out the findings of Allison et al. (1998b) who showed that the lack of positive effects on yield suggests that cover crops are not a financially viable option for sugar beet farmers as costs of establishment are not recouped by an increase in yield. However, if agricultural policy continues in the direction of using techniques to improve soil health through subsidising their use, the financial cost to the farmer may be outweighed by the financial reward of environmental subsidy.

7.5.2 Implications for policy makers

We have found that, excluding periods of extreme weather and unreasonable soil constraints, cover crops can have a positive or neutral effect on sugar beet yield. Furthermore, the effects on earthworm abundance and management of autumn rainfall suggest that inclusion of cover crops are beneficial to the soil environment. While we have not explored the long term effects of cover crops on the environment, our findings in combination with reports such as Cooper et al. (2017) suggest that including cover crops in the crop rotation is a viable option for improving soil structure and nutrient content in the short term.

Our findings show that a combination of cover crop species has no benefit to a single species cover crop and hence do not support the current EFA regulations. It is likely that the short growing period of the autumn sown cover crops does not allow sufficient time for species richness to outweigh the benefits of producing a large food source for soil fauna.

Chapter 8: Conclusions and suggestions for future work

8.1 Conclusions

Cover crops were able to alter soil aggregation. This was governed by root density, soil moisture and soil texture. Through the growth of roots, a greater proportion of aggregates was produced which is a likely result of both direct root growth and wetting and drying cycles caused by plant water uptake. This effect was more pronounced when clay content in field soil was relatively high, reflecting the high plasticity of clay compared to sand.

Cover crops had a significant effect on soil moisture during their growth. Larger cover crops were able to have a greater influence on soil moisture as a result of both greater root exploration and higher water demand.

The influence of cover crops on soil moisture did not directly affect the water availability to the sugar beet crop. This is a result of destruction date of the cover crop allowing sufficient time for soil to reach field capacity.

The presence of cover crops increased earthworm populations in some conditions. This was determined by the presence of a food supply for earthworms and the soil moisture being favourable to earthworm activity.

There was no benefit in terms of growth or influence on the soil structure, root growth or earthworm population of combining multiple cover crop species.

Cover crops were able to increase soil porosity on soils with a high sand content which led to better water uptake by the sugar beet and higher yields. This effect was not seen on soil with a higher clay content as a result of soil constraints during drought conditions.

Measurements of soil conductivity were a useful proxy for water uptake by both cover crops and sugar beet and indicated areas of the experiments that took up more water resulted in higher sugar beet yield.

The direct effect of cover crops on sugar beet yield were mixed and tended to be determined by water supply suggesting that water is still the most important environmental factor limiting sugar beet yield.

In reflection of the hypotheses set out at the start of the project it is reasonable to accept that the influence of cover crops on the soil structure is determined by a combination of environmental factors. The project has consistently shown that the volume of soil and the soil type has a considerable impact on the influence that cover crops roots have on the soil structure. Further to this, the variable results of the field experiments confirm that air temperature, soil moisture and water uptake will have a huge influence on the ability of cover crops to change the soil structure.

It is unlikely that the growth of cover crops will have had a detrimental effect on the soil structure, their variable results in years where autumn soil moisture is high and temperatures are low, the effect on cover crop growth will likely result in farmers questioning their investment of money and time at least in the short term.

When comparing results between all chapters and the published literature, we can accept that the success of cover crops will depend on soil texture. When experiments were conducted on soils with relatively high clay content, the effect of cover crop roots on the soil was more permanent. However, it was on soils with relatively low clay content where the effect of cover crops on sugar beet was measured. This shows that when we consider whether cover crops can result in between water and nutrient uptake we can say ‘sometimes’.

When detailed analysis was made of species interactions we found there was no great impact on the overall growth of the cover crop. Based on the literature and the findings of this project the main aim for cover crops is to maximise root growth rather than species diversity.

8.2 Suggestions for further work

Given the direction of agricultural and environmental policy it is likely that there will be increased focus on techniques such as cover crops and improving soil health to deliver ‘public goods’. However, it is important that uptake and use of these methods are optimised to ensure that there is not a waste of resources either for government or farmers.

From this work, and previous studies from the UK and Europe, it is clear that there is an appetite and the potential for cover crops to deliver benefits to crop yield. However, the mixed results from this project suggest that cover cropping in its most basic form may not be sufficient to produce guaranteed crop yield increases.

I suggest that further research should focus on using cover cropping in combination with strip cultivation. This may allow benefits of cover crop roots to be realised by the following crop rather than being removed during the cultivation practices prior to crop establishment.

Further to this, we saw positive results of including sheep grazing as a method of cover crop destruction. Further research should focus on the timing of grazing to prevent compaction and optimise return of nitrate to the soil for the following crop. In addition, a study of the most effective cover crop grazing systems would be beneficial to maximise the nutritional value for stock and the benefits to soil structure.

In line with sugar beet demands for water and the increasing risk of extreme drought it would be useful to invest time into understanding methods that can improve soil water reserves and movement through the soil profile to avoid water scarcity during the summer months in particular.

In combination with understanding soil-water relations for sugar beet water uptake, it would be useful at the same time to develop a model for remote soil moisture sensing that will allow predictions to be made for optimum tillage range to prevent damage to the soil structure. This could also be used to predict the timing of drilling and application of irrigation in some systems.

Chapter 9: References

ABDOLLAHI, L. & MUNKHOLM, L. J. 2014. Tillage System and Cover crop effects on soil quality: i. Chemical, mechanical, and biological properties. *Soil Science Society of America Journal,* 78**,** 262-270.

ALLISON, M. F., ARMSTRONG, M. J., JAGGARD, K. W. & TODD, A. D. 1998a. Integration of nitrate cover crops into sugarbeet (Beta vulgaris) rotations. I. Management and effectiveness of nitrate cover crops. *Journal of Agricultural Science,* 130**,** 53-60.

ALLISON, M. F., ARMSTRONG, M. J., JAGGARD, K. W. & TODD, A. D. 1998b. Integration of nitrate cover crops into sugarbeet (Beta vulgaris) rotations. II. Effect of cover crops on growth, yield and N requirement of sugarbeet. *Journal of Agricultural Science,* 130**,** 61-67.

ANGERS, D. A. & CHENU, C. 1998. Dynamics of soil aggregation and c sequestration. *In:* LAL, R., KIMBLE, J. M., FOLLETT, R. F. & STEWART, B. A. (eds.) *Soil Processes and the Carbon Cycle.* London, UK: CRC Press.

ARONSSON, H., HANSEN, E. M., THOMSEN, I. K., LIU, J., OGAARD, A. F., KANKANEN, H. & ULEN, B. 2016. The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. *Journal of Soil and Water Conservation,* 71**,** 41-55.

ARVIDSSON, J., BOLENIUS, E. & CAVALIERI, K. M. V. 2012. Effects of compaction during drilling on yield of sugar beet (Beta vulgaris L.). *European Journal of Agronomy,* 39**,** 44-51.

ASHER, M. J. C. & HANSON, L. E. 2006. Fungal and bacterial diseases. *In:* DRAYCOTT, A. P. (ed.) *Sugar Beet.* London: Blackwell.

ATKINSON, B. S., SPARKES, D. L. & MOONEY, S. J. 2007. Using selected soil physical properties of seedbeds to predict crop establishment. *Soil & Tillage Research,* 97**,** 218-228.

ATKINSON, B. S., SPARKES, D. L. & MOONEY, S. J. 2009. Effect of seedbed cultivation and soil macrostructure on the establishment of winter wheat (Triticum aestivum). *Soil and Tillage Research,* 103**,** 291-301.

ATTERBERG, A. 1905. *Die rationelle Klassifikation der Sande und Kiese*.

AZOOZ, R. H. & ARSHAD, M. A. 1996. Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. *Canadian Journal of Soil Science,* 76**,** 143-152.

BACHMANN, J. & HARTGE, K. H. 2006. Estimating soil stress distribution by using depth-dependent soil bulk-density data. *Journal of Plant Nutrition and Soil Science,* 169**,** 233-238.

BAO, Y., AGGARWAL, P., ROBBINS, N. E., STURROCK, C. J., THOMPSON, M. C., TAN, H. Q., THAM, C., DUAN, L. N., RODRIGUEZ, P. L., VERNOUX, T., MOONEY, S. J., BENNETT, M. J. & DINNENY, J. R. 2014. Plant roots use a patterning mechanism to position lateral root branches toward available water. *Proceedings of the National Academy of Sciences of the United States of America,* 111**,** 9319-9324.

BARNES, B. T. & ELLIS, F. B. 1979. Effects of different methods of cultivation and direct drilling, and disposal of straw residues, on populations of earthworms. *Journal of Soil Science,* 30**,** 669-679.

BBRO 2019. *BBRO Reference Book,* Norwich, BBRO.

BELLAMY, P. H., LOVELAND, P. J., BRADLEY, R. I., LARK, R. M. & KIRK, G. J. D. 2005. Carbon losses from all soils across England and Wales 1978–2003. *Nature,* 437**,** 245-248.

BENGOUGH, A. G., BRANSBY, M. F., HANS, J., MCKENNA, S. J., ROBERTS, T. J. & VALENTINE, T. A. 2006. Root responses to soil physical conditions; growth dynamics from field to cell. *Journal of Experimental Botany,* 57**,** 437-447.

BENGOUGH, A. G. & MULLINS, C. E. 1990. Mechanical impedance to root growth: a review of experimental techniques and root growth responses. *Journal of Soil Science,* 41**,** 341-358.

BERNIER, G., HAVELANGE, A., HOUSSA, C., PETITJEAN, A. & LEJEUNE, P. 1993. Physiological signals that induce flowering. *Plant Cell,* 5**,** 1147-1155.

BERTRAND, M., BAROT, S., BLOUIN, M., WHALEN, J., DE OLIVEIRA, T. & ROGER-ESTRADE, J. 2015. Earthworm services for cropping systems. A review. *Agronomy for Sustainable Development,* 35**,** 553-567.

BEVEN, K. & GERMANN, P. 1982. Macropores and water flow in soils. *Water Resources Research,* 18**,** 1311-1325.

BLACKWELL, P. S., GREEN, T. W. & MASON, W. K. 1990. Responses of biopore channels from roots to compression by vertical stresses. *Soil Science Society of America Journal,* 54**,** 1088-1091.

BLUM, A. 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field Crops Research,* 112**,** 119-123.

BLUNK, S., DE HEER, M. I., STURROCK, C. J. & MOONEY, S. J. 2018. Soil seedbed engineering and its impact on germination and establishment in sugar beet (Beta vulgaris L.) as affected by seed-soil contact. *Seed Science Research,* 28**,** 236-244.

BLUNK, S., MALIK, A. H., DE HEER, M. I., EKBLAD, T., BUSSELL, J., SPARKES, D., FREDLUND, K., STURROCK, C. J. & MOONEY, S.

J. 2017. Quantification of seed-soil contact of sugar beet (Beta vulgaris) using X-ray Computed Tomography. *Plant Methods,* 13**,** 14.

BODNER, G., HIMMELBAUER, M., LOISKANDL, W. & KAUL, H.-P. 2010. Improved evaluation of cover crop species by growth and root factors. *Agronomy for Sustainable Development,* 30**,** 455-464.

BODNER, G., LEITNER, D. & KAUL, H. P. 2014. Coarse and fine root plants affect pore size distributions differently. *Plant and soil,* 380**,** 133-151.

BODNER, G., LOISKANDL, W., BUCHAN, G. & KAUL, H. P. 2008. Natural and management-induced dynamics of hydraulic conductivity along a cover-cropped field slope. *Geoderma,* 146**,** 317-325.

BONKOWSKI, M., VILLENAVE, C. & GRIFFITHS, B. 2009. Rhizosphere fauna: the functional and structural diversity of intimate interactions of soil fauna with plant roots. *Plant and Soil,* 321**,** 213-233.

BRELAND, T. A. 1995. Green manuring with clover and ryegrass catch crops undersown in spring wheat: Effects on soil structure. *Soil Use and Management,* 11**,** 163-167.

BRERETON, J. C., MCGOWAN, M. & DAWKINS, T. C. K. 1986. The relative sensitivity of spring barley, spring field beans and sugar beet crops to soil compaction. *Field Crops Research,* 13**,** 223-237.

BROWN, K. F. & BISCOE, P. V. 1985. Fibrous root-growth and water-use of sugar-beet. *Journal of Agricultural Science,* 105**,** 679-691.

BRUST, J., CLAUPEIN, W. & GERHARDS, R. 2014. Growth and weed suppression ability of common and new cover crops in Germany. *Crop Protection,* 63**,** 1-8.

BURKY & BISCOE. Stickstoff imR¨ubenblatt und N-Translokation aus

alternden Bl¨attern. IIRB Winter Congress, 1983 Brussels. IIRB, 63-75.

BURR-HERSEY, J. E., MOONEY, S. J., BENGOUGH, A. G., MAIRHOFER, S. & RITZ, K. 2017. Developmental morphology of cover crop species exhibit contrasting behaviour to changes in soil bulk density, revealed by X-ray computed tomography. *Plos One,* 12**,** 18.

CARDINALE, B. J., MATULICH, K. L., HOOPER, D. U., BYRNES, J. E., DUFFY, E., GAMFELDT, L., BALVANERA, P., O'CONNOR, M. I. & GONZALEZ, A. 2011. The functional role of producer diversity in ecosystems. *American Journal of Botany,* 98**,** 572-592.

CHEN, G. H. & WEIL, R. R. 2010. Penetration of cover crop roots through compacted soils. *Plant and Soil,* 331**,** 31-43.

CICEK, H., MARTENS, J. R. T., BAMFORD, K. C. & ENTZ, M. H. 2015. Late-season catch crops reduce nitrate leaching risk after grazed green manures but release N slower than wheat demand. *Agriculture Ecosystems & Environment,* 202**,** 31-41.

CICEK, H., THIESSEN MARTENS, J. R., BAMFORD, K. C. & ENTZ, M. H. 2014. Effects of grazing two green manure crop types in organic farming systems: N supply and productivity of following grain crops. *Agriculture, Ecosystems & Environment,* 190**,** 27-36.

CLARK, J. T., RUSSELL, J. R., KARLEN, D. L., SINGLETON, P. L., BUSBY, W. D. & PETERSON, B. C. 2004. Soil surface property and soybean yield response to corn stover grazing. *Agronomy Journal,* 96**,** 1364-1371.

CLARK, L. J., WHALLEY, W. R. & BARRACLOUGH, P. B. 2003. How do roots penetrate strong soil? *Plant and Soil,* 255**,** 93-104.

COGMAN, R. & MORRIS, N. 2009. Beet Cyst Nematode - Living with the enemy. *British Sugar Beet Review,* 77**,** 10-14.

COLLINS, M., KNUTTI, R., ARBLASTER, J., DUFRESNE, J. L., FICHEFET, T., FRIEDLINGSTEIN, P., GAO, X. J., GUTOWSKI, W. J., JOHNS, T., KRINNER, G., SHONGWE, M., TEBALDI, C.,

WEAVER, A. J., WEHNER, M., ALLEN, M. R., ANDREWS, T., BEYERLE, U., BITZ, C. M., BONY, S., BOOTH, B. B., BROOKS, H. E., BROVKIN, V., BROWNE, O., BRUTEL-VUILMET, C., CANE, M., CHADWICK, R., COOK, E., COOK, K. H., EBY, M., FASULLO, J., FISCHER, E. M., FOREST, C. E., FORSTER, P., GOOD, P., GOOSSE, H., GREGORY, J. M., HEGERL, G. C., HEZEL, P. J., HODGES, K. I., HOLLAND, M. M., HUBER, M., HUYBRECHTS, P., JOSHI, M., KHARIN, V., KUSHNIR, Y., LAWRENCE, D. M., LEE, R. W., LIDDICOAT, S., LUCAS, C., LUCHT, W., MAROTZKE, J., MASSONNET, F., MATTHEWS, H. D., MEINSHAUSEN, M., MORICE, C., OTTO, A., PATRICOLA, C. M., PHILIPPON-BERTHIER, G., PRABHAT, RAHMSTORF, S., RILEY, W. J., ROGELJ, J., SAENKO, O., SEAGER, R., SEDLACEK, J., SHAFFREY, L. C., SHINDELL, D., SILLMANN, J., SLATER, A., STEVENS, B., STOTT, P. A., WEBB, R., ZAPPA, G. & ZICKFELD, K. 2014. Long-term climate change: projections, commitments and irreversibility, Cambridge, Cambridge Univ Press.

COOPER, R. J., HAMA-AZIZ, Z., HISCOCK, K. M., LOVETT, A. A., DUGDALE, S. J., SUNNENBERG, G., NOBLE, L., BEAMISH, J. & HOVESEN, P. 2017. Assessing the farm-scale impacts of cover crops and non-inversion tillage regimes on nutrient losses from an arable catchment. *Agriculture Ecosystems & Environment,* 237**,** 181-193.

COUSENS, R. D., JOHNSON, M. P., WEAVER, S. E., MARTIN, T. D. & BLAIR, A. M. 1992. Comparative rates of emergence and leaf appearance in wild oats (Avena-fatua), winter barley (Hordeum-sativum) and winter-wheat (Triticum-aestivum). *Journal of Agricultural Science,* 118**,** 149-156.

CRAINE, J. M. & DYBZINSKI, R. 2013. Mechanisms of plant competition for nutrients, water and light. *Functional Ecology,* 27**,** 833-840.

CRITTENDEN, S. J., ESWARAMURTHY, T., DE GOEDE, R. G. M., BRUSSAARD, L. & PULLEMAN, M. M. 2014. Effect of tillage on earthworms over short- and medium-term in conventional and organic farming. *Applied Soil Ecology,* 83**,** 140-148.

CROTTY, F. How can soil-improving cropping systems reduce compaction? Assessing mechanical methods in comparison to increasing root uptake and growth through biological ammendment. Soil Improvement: impact of Management Practices on Soil Function and Quality, 2018 Cambridge. Association of Applied Biologists.

CROTTY, V. F. & STOATE, C. 2019. The legacy of cover crops on the soil habitat and ecosystem services in a heavy clay, minimum tillage rotation. *Food and Energy Security*.

DAPAAH, H. K. & VYN, T. J. 1998. Nitrogen fertilization and cover crop effects on soil structural stability and corn performance. *Communications in Soil Science and Plant Analysis,* 29**,** 2557-2569.

DE KOEIJER, K. J. & VAN DER WERF, W. 1995. Effect of beet yellowing viruses on light interception and light use efficiency of the sugarbeet crop. *Crop Protection,* 14**,** 291-297.

DEFRA 2018. Basic payment scheme: rules for 2019. *In:* DEFRA (ed.). London: UK Government.

DELTA-T 1995. User manual for the delta-t root washer. *In:* WEBB, N. (ed.) 1 ed. Cambridge: Delta-t devices.

DETHERIDGE, A. P., BRAND, G., FYCHAN, R., CROTTY, F. V., SANDERSON, R., GRIFFITH, G. W. & MARLEY, C. L. 2016. The legacy effect of cover crops on soil fungal populations in a cereal rotation. *Agriculture Ecosystems & Environment,* 228**,** 49-61.

DEXTER, A. R. 1987. Compression of soil around roots. *Plant and Soil,* 97**,** 401-406.

DEXTER, A. R. 1988. Advances in characterization of soil structure. *Soil and Tillage Research,* 11**,** 199-238.

DEXTER, A. R. 1997. Physical properties of tilled soils. *Soil & Tillage Research,* 43**,** 41-63.

DEXTER, A. R. & BIRD, N. R. A. 2001. Methods for predicting the optimum and the range of soil water contents for tillage based on the water retention curve. *Soil & Tillage Research,* 57**,** 203-212.

DHIMA, K. V., VASILAKOGLOU, I. B., ELEFTHEROHORINOS, I. G. & LITHOURGIDIS, A. S. 2006. Allelopathic potential of winter cereal cover crop mulches on grass weed suppression and sugarbeet development. *Crop Science,* 46**,** 1682-1691.

DUBE, E., CHIDUZA, C. & MUCHAONYERWA, P. 2014. High biomass yielding winter cover crops can improve phosphorus availability in soil. *South African Journal of Science,* 110**,** 60-63.

DUNCAN, A. J., BACHEWE, F., MEKONNEN, K., VALBUENA, D., RACHIER, G., LULE, D., BAHTA, M. & ERENSTEIN, O. 2016. Crop residue allocation to livestock feed, soil improvement and other uses along a productivity gradient in Eastern Africa. *Agriculture Ecosystems & Environment,* 228**,** 101-110.

DURR, C. & AUBERTOT, J. N. 2000. Emergence of seedlings of sugar beet (Beta vulgaris L.) as affected by the size, roughness and position of aggregates in the seedbed. *Plant and Soil,* 219**,** 211-220.

DURR, C., AUBERTOT, J. N., RICHARD, G., DUBRULLE, P., DUVAL, Y. & BOIFFIN, J. 2001. SIMPLE: A model for SIMulation of PLant emergence predicting the effects of soil tillage and sowing operations. *Soil Science Society of America Journal,* 65**,** 414-423.

DURRANT, M. J. & JAGGARD, K. W. 1988. Sugar-beet seed advancement to increase establishment and decrease bolting. *Journal of Agricultural Science,* 110**,** 367-374.

DURRANT, M. J. & LOADS, A. H. 1986. THE EFFECT OF PELLET STRUCTURE ON THE GERMINATION AND EMERGENCE OF SUGAR-BEET SEED. *Seed Science and Technology,* 14**,** 343-353.

DURRANT, M. J., MASH, S. J. & JAGGARD, K. W. 1993. Effects of seed advancement and sowing date on establishment, bolting and yield of sugar-beet. *Journal of Agricultural Science,* 121**,** 333-341.

EASTON, Z. & BOCK, E. 2016. Soil and Water Relationships. *In:* UNIVERSITY, V. S. (ed.). Virginia: Virginia State University.

EDMONDSON, J. L., DAVIES, Z. G., GASTON, K. J. & LEAKE, J. R. 2014. Urban cultivation in allotments maintains soil qualities adversely affected by conventional agriculture. *Journal of Applied Ecology,* 51**,** 880-889.

EDWARDS, C. A. & BOHLEN, P. J. 1996. The influence of environmental factors on earthworms. *In:* EDWARDS, C. A. & BOHLEN, P. J. (eds.) *Biology and Ecology of Earthworms.* Third ed. London, UK: Chapman & Hall.

EHLERS, W. 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. *Soil Science,* 119**,** 242-249.

ELLIS, F. B., ELLIOTT, J. G., POLLARD, F., CANNELL, R. Q. & BARNES, B. T. 1979. COMPARISON OF DIRECT DRILLING, REDUCED CULTIVATION AND PLOWING ON THE GROWTH OF CEREALS .3. WINTER-WHEAT AND SPRING BARLEY ON A CALCAREOUS CLAY. *Journal of Agricultural Science,* 93**,** 391-&.

EMERSON, W. 1995. Water-retention, organic-C and soil texture. *Soil Research,* 33**,** 241-251.

EMERSON, W. W. 1954. The determination of the stability of soil crumbs. *Journal of Soil Science,* 5**,** 233-250.

ETHERIDGE, R. D., PESTI, G. M. & FOSTER, E. H. 1998. A comparison of nitrogen values obtained utilizing the Kjeldahl nitrogen and Dumas combustion methodologies (Leco CNS 2000) on samples typical of an animal nutrition analytical laboratory. *Animal Feed Science and Technology,* 73**,** 21-28.

FAO. 2014. *UK Sugar beet production Statistics 2014* [Online]. www.fao.org: FAO, United Nations. [Accessed 13/12/2018 2018].

FAO. 2016. *Land use in the United Kingdom* [Online]. FAO.org: Food and Agriculture Organisation, United Nations. Available: http://www.fao.org/faostat/ [Accessed 10/06/2018 2018].

FAO. 2018. *Global sugar production* [Online]. www.fao.org: Food and Agriculture Organisation, United Nations. [Accessed 13/12/2018 2018].

FINNEY, D. M., WHITE, C. M. & KAYE, J. P. 2016. Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. *Agronomy Journal*, 108**,** 39-52.

FITTERS, T. F. J., BUSSELL, J. S., MOONEY, S. J. & SPARKES, D. L. 2017. Assessing water uptake in sugar beet (Beta vulgaris) under different watering regimes. *Environmental and Experimental Botany,* 144**,** 61-67.

FRANZLUEBBERS, A. J. & ARSHAD, M. A. 1996. Water-stable aggregation and organic matter in four soils under conventional and zero tillage. *Canadian Journal of Soil Science*, 76**,** 387-393.

FREDLUND, D. G. & XING, A. Q. 1994. Equations for the soil-water characteristic curve. *Canadian Geotechnical Journal,* 31**,** 521-532.

FUEKI, N. & TAKEUCHI, H. 2010. Difference in vertical root distribution of sugar beet (Beta vulgaris L.) and its relationship to soil properties in four typical soil profiles in Hokkaido, Japan. *Soil Science and Plant Nutrition,* 56**,** 745-749.

GAUER, E., SHAYKEWICH, C. F. & STOBBE, E. H. 1982. Soil-temperature and soil-water under zero tillage in manitoba. *Canadian Journal of Soil Science,* 62**,** 311-325.

GÉNARD, T., ETIENNE, P., DIQUÉLOU, S., YVIN, J.-C., REVELLIN, C. & LAÎNÉ, P. 2017. Rapeseed-legume intercrops: plant growth and nitrogen balance in early stages of growth and development. *Heliyon,* 3**,** e00261.

GISH, T. J. & JURY, W. A. 1983. Effect of plant roots and root channels on solute transport. *American Society of Agricultural Engineers,* 26.

GLAB, T. & KULIG, B. 2008. Effect of mulch and tillage system on soil porosity under wheat (Triticum aestivum). *Soil & Tillage Research,* 99**,** 169-178.

GOSS, M. J. 1977. Effects of mechanical impedance on root growth in barley (hordeum vulgare l.): i. Effects on the elongation and branching of seminal root axes. *Journal of Experimental Botany,* 28**,** 96-111.

GÖTZE, P., RÜCKNAGEL, J., JACOBS, A., MÄRLÄNDER, B., KOCH, H.-J., HOLZWEIßIG, B., STEINZ, M. & CHRISTEN, O. 2016. Sugar beet rotation effects on soil organic matter and calculated humus balance in Central Germany. *European Journal of Agronomy,* 76**,** 198-207.

GREENWOOD, D. J., GERWITZ, A., STONE, D. A. & BARNES, A. 1982. Root development of vegetable crops. *Plant and Soil,* 68**,** 75-96.

GREENWOOD, K. L. & MCKENZIE, B. M. 2001. Grazing effects on soil physical properties and the consequences for pastures: a review. *Australian Journal of Experimental Agriculture,* 41**,** 1231-1250.

GREGORY, P. J., BENGOUGH, A. G., GEORGE, T. S. & HALLETT, P. D. 2013. Rhizosphere engineering by plants: quantifying soil-root interactions. *In:* TIMLIN, D. & AHUJA, L. R. (eds.) *Enhancing*

Understanding and Quantification of Soil-Root Growth Interactions, Vol 4. Madison: Amer Soc Agronomy.

GRINDLAY, D. 1995. *Principles governing the ability of cover crop species to trap nitrogen.* Ph. D Crop science, University of Nottingham

GUIDI, G., POGGIO, G. & PETRUZZELLI, G. 1985. The porosity of soil aggregates from bulk soil and from soil adhering to roots. *Plant and Soil,* 87**,** 311-314.

GUMMERSON, R. J. 1989. Seed-bed cultivations and sugar-beet seedling emergence. *Journal of Agricultural Science,* 112**,** 159-169.

GYSSELS, G., POESEN, J., BOCHET, E. & LI, Y. 2005. Impact of plant roots on the resistance of soils to erosion by water: a review. *Progress in Physical Geography,* 29**,** 189-217.

HAKANSSON, I., HENRIKSSON, L. & BLOMQUIST, J. E. 2006. Soil Tillage and Crop Establishment. *In:* DRAYCOTT, A. P. (ed.) *Sugar Beet.* Oxford: Blackwell Publishinh Ltd.

HAKANSSON, I., VOORHEES, W. B. & RILEY, H. 1988. Vehicle and wheel factors influencing soil compaction and crop response in different traffic regimes. *Soil & Tillage Research,* 11**,** 239-282.

HALLAM, A., ANDERSON, I. C. & BUXTON, D. R. 2001. Comparative economic analysis of perennial, annual, and intercrops for biomass production. *Biomass and Bioenergy,* 21**,** 407-424.

HAN, E., KAUTZ, T., PERKONS, U., UTEAU, D., PETH, S., HUANG, N., HORN, R. & KOPKE, U. 2015. Root growth dynamics inside and outside of soil biopores as affected by crop sequence determined with the profile wall method. *Biology and Fertility of Soils,* 51**,** 847-856.

HARUNA, S. I., ANDERSON, S. H., NKONGOLO, N. V. & ZAIBON, S. 2018. Soil hydraulic properties: influence of tillage and cover crops. *Pedosphere,* 28**,** 430-442.

HAYNES, R. J. & NAIDU, R. 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems,* 51**,** 123-137.

HAYNES, R. J. & SWIFT, R. S. 1990. Stability of soil aggregates in relation to organic-constituents and soil-water content. *Journal of Soil Science,* 41**,** 73-83.

HEBBLETHWAITE, P. D. & MCGOWAN, M. 1980. The effects of soil compaction on the emergence, growth and yield of sugar beet and peas. *Journal of the Science of Food and Agriculture,* 31**,** 1131-1142.

HELLIWELL, J. R., STURROCK, C. J., MILLER, A. J., WHALLEY, W. R. & MOONEY, S. J. 2019. The role of plant species and soil condition in the structural development of the rhizosphere. *Plant Cell and Environment,* 42**,** 1974-1986.

HENDERSON, C. W. L. 1989. Lupin as a biological plough - evidence for, and effects on wheat growth and yield. *Australian Journal of Experimental Agriculture,* 29**,** 99-102.

HILL, E. C., RENNER, K. A. & SPRAGUE, C. L. 2016. Cover crop impact on nitrogen availability and dry bean in an organic system. *Agronomy Journal,* 108**,** 329-341.

HOFFMANN, C. M. & KENTER, C. 2018. Yield potential of sugar beet - have we hit the ceiling? *Frontiers in Plant Science,* 9**,** 6.

HOFFMANN, C. M. & SCHNEPEL, K. 2016. Susceptibility to root tip breakage increases storage losses of sugar beet genotypes. *Sugar Industry-Zuckerindustrie,* 141**,** 625-632.

HOOPER, D. U., CHAPIN III, F. S., EWEL, J. J., HECTOR, A., INCHAUSTI, P., LAVOREL, S., LAWTON, J. H., LODGE, D. M., LOREAU, M., NAEEM, S., SCHMID, B., SETÄLÄ, H., SYMSTAD, A. J., VANDERMEER, J. & WARDLE, D. A. 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecological Monographs,* 75**,** 3-35.

HORN, R., DOMZAL, H., SLOWINSKAJURKIEWICZ, A. & VANOUWERKERK, C. 1995. Soil compaction processes and their effects on the structure of arable soils and the environment. *Soil & Tillage Research,* 35**,** 23-36.

HUDSON, B. D. 1994. Soil organic-matter and available water capacity. *Journal of Soil and Water Conservation,* 49**,** 189-194.

HUNTER, J. R. & ERICKSON, A. E. 1952. Relation of seed germination to soil moisture tension. *Agronomy Journal,* 44**,** 107-109.

JAGGARD, K. 1979. *The effect of plant distribution on yield of sugar beet.* Ph.D, University of Nottingham.

JAGGARD, K. & QI, A. 2006. Agronomy. *In:* DRAYCOTT, P. (ed.) *Sugar beet.* Oxford: Blackwell.

JAGGARD, K. W. 1977. Effects of soil density on yield and fertilizer requirement of sugar-beet. *Annals of Applied Biology,* 86**,** 301-312.

JAGGARD, K. W., CLARK, C. J. A. & DRAYCOTT, A. P. 1999. The weight and processing quality of components of the storage roots of sugar beet (Beta vulgaris L). *Journal of the Science of Food and Agriculture,* 79**,** 1389-1398.

JAGGARD, K. W., DEWAR, A. M. & PIDGEON, J. D. 1998. The relative effects of drought stress and virus yellows on the yield of sugarbeet in the UK, 1980-95. *Journal of Agricultural Science,* 130**,** 337-343.

JAGGARD, K. W., QI, A., MILFORD, G. F. J., CLARK, C. J. A., OBER, E. S., WALTERS, C. & BURKS, E. 2011. Determining the optimal population density of sugarbeet crops in England. *International Sugar Journal,* 113**,** 114-119.

JAGGARD, K. W., QI, A. & OBER, E. S. 2009. Capture and use of solar radiation, water, and nitrogen by sugar beet (Beta vulgaris L.). *Journal of Experimental Botany,* 60**,** 1919-1925.

JAGGARD, K. W. & WERKER, A. R. 1999. An evaluation of the potential benefits and costs of autumn-sown sugarbeet in NW Europe. *Journal of Agricultural Science,* 132**,** 91-102.

JAGGARD, K. W., WICKENS, R., WEBB, D. J. & SCOTT, R. K. 1983. Effects of sowing date on plant establishment and bolting and the influence of these factors on yields of sugar-beet. *Journal of Agricultural Science,* 101**,** 147-161.

JAHN, R. 2006. Guidelines for soil description. *In:* NATIONS, F. A. A. O. O. T. U. (ed.) Fourth ed. Rome: Food and Agriculture Organisation of the United Nations.

JAKOBSEN, B. F. & DEXTER, A. R. 1988. Influence of biopores on root-growth, water-uptake and grain-yield of wheat (triticum-aestivum) based on predictions from a computer-model. *Biology and Fertility of Soils,* 6**,** 315-321.

JANE, P. B. & PUTNAM, A. R. 1986. Evidence for allelopathy by residues and aqueous extracts of rye (secale cereale). *Weed Science,* 34**,** 384-390.

JANZEN, H. H. & RADDER, G. D. 1989. Nitrogen mineralization in a green manure-amended soil as influenced by cropping history and subsequent crop. *Plant and Soil,* 120**,** 125-131.

JÉGOU, D., CLUZEAU, D., HALLAIRE, V., BALESDENT, J. & TRÉHEN, P. 2000. Burrowing activity of the earthworms Lumbricus terrestris and Aporrectodea giardi and consequences on C transfers in soil. *European Journal of Soil Biology,* 36**,** 27-34.

JENNINGS, A. J. & FULLER, M. P. 2003. Arable cropping. *In:* SOFFE, R. (ed.) *The Agricultural Notebook.* 20th ed. Oxford, UK: Blackwell.

JOHNSTON, A. E. 1986. Soil organic-matter, effects on soils and crops. *Soil Use and Management,* 2**,** 97-105.

JOHNSTON, A. E., POULTON, P. R. & COLEMAN, K. 2009. Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. *In:* SPARKS, D. L. (ed.) *Advances in Agronomy, Vol 101.* San Diego: Elsevier Academic Press Inc.

JOHNSTON, A. E., POULTON, P. R., COLEMAN, K., MACDONALD, A. J. & WHITE, R. P. 2017. Changes in soil organic matter over 70 years in continuous arable and ley-arable rotations on a sandy loam soil in England. *European Journal of Soil Science,* 68**,** 305-316.

KAUFMANN, M., TOBIAS, S. & SCHULIN, R. 2010. Comparison of critical limits for crop plant growth based on different indicators for the state of soil compaction. *Journal of Plant Nutrition and Soil Science,* 173**,** 573-583.

KAUTZ, T. 2015. Research on subsoil biopores and their functions in organically managed soils: A review. *Renewable Agriculture and Food Systems,* 30**,** 318-327.

KAY, B. D. 1998. Soil Structure and Organic Carbon: A Review. *In:* LAL, R., KIMBLE, J. M., FOLLETT, R. F. & STEWART, B. A. (eds.) *Soil Processes and the Carbon Cycle.* London, UK: CRC Press.

KELLER, T. & DEXTER, A. R. 2012. Plastic limits of agricultural soils as functions of soil texture and organic matter content. *Soil Research,* 50**,** 7-17.

KEMPNER, W. D. & ROSENAU, R. C. 1986. Aggregate Stability and Size Distribution. *In:* KLUTE, A. (ed.) *Methods of Soil Analysis Part 1.* 2 ed. Wisconsin USA: Madison.

KHAN, Z. R., MIDEGA, C. A. O., BRUCE, T. J. A., HOOPER, A. M. & PICKETT, J. A. 2010. Exploiting phytochemicals for developing a ‘push–pull’ crop protection strategy for cereal farmers in Africa. *Journal of Experimental Botany,* 61**,** 4185-4196.

KINET, J. M. 1972. Sinapis-alba, a plant requiring a single long day or a single short day for flowering. *Nature,* 236**,** 406-&.

KNOTT, C. M. 1996. The effect of cover crops on the establishment and yield of vining peas and on nitrate leaching. *Journal of Agricultural Science,* 126**,** 471-479.

KOCH, H. J. 2009. Relations between soil structural properties and sugar beet yield on

a Luvisol. *Pflanzenbauwissenschaften,* 13**,** 49-59.

KOCH, H. J., DIECKMANN, J., BUCHSE, A. & MARLANDER, B. 2009. Yield decrease in sugar beet caused by reduced tillage and direct drilling. *European Journal of Agronomy,* 30**,** 101-109.

KORUCU, T., SHIPITALO, M. J. & KASPAR, T. C. 2018. Rye cover crop increases earthworm populations and reduces losses of broadcast, fall-applied, fertilizers in surface runoff. *Soil & Tillage Research,* 180**,** 99-106.

LAINE, P., OURRY, A., MACDUFF, J., BOUCAUD, J. & SALETTE, J. 1993. Kinetic-parameters of nitrate uptake by different catch crop species - effects of low-temperatures or previous nitrate starvation. *Physiologia Plantarum,* 88**,** 85-92.

LARNEY, F. J., FORTUNE, R. A. & COLLINS, J. F. 1988. Intrinsic soil physical parameters influencing intensity of cultivation procedures for sugar-beet seedbed preparation. *Soil & Tillage Research,* 12**,** 253-267.

LAUFER, D. & KOCH, H. J. 2017. Growth and yield formation of sugar beet (Beta vulgaris L.) under strip tillage compared to full width tillage on silt loam soil in Central Europe. *European Journal of Agronomy,* 82**,** 182-189.

LAWLEY, Y. E., TEASDALE, J. R. & WEIL, R. R. 2012. The Mechanism for weed suppression by a forage radish cover crop. *Agronomy Journal,* 104**,** 205-214.

LAYTON, J. B., SKIDMORE, E. L. & THOMPSON, C. A. 1993. Winter-associated changes in dry-soil aggregation as influenced by management. *Soil Science Society of America Journal,* 57**,** 1568-1572.

LEE, K. E. 1985. The Physical Environment: Soil Texture. *In:* LEE, K. E. (ed.) *Earthworms: Their ecology and relationships with soils and land use.* First ed. London: Academic Press.

LEHRSCH, G. A., LENTZ, R. D. & KINCAID, D. C. 2005. Polymer and sprinkler droplet energy effects on sugar beet emergence, soil penetration resistance, and aggregate stability. *Plant and Soil,* 273**,** 1-13.

LEROY, B. L. M., SCHMIDT, O., VAN DEN BOSSCHE, A., REHEUL, D. & MOENS, M. 2008. Earthworm population dynamics as influenced by the quality of exogenous organic matter. *Pedobiologia,* 52**,** 139-150.

LI, Y. & GHODRATI, M. 1994. Preferential transport of nitrate through soil columns containing root channels. *Soil Science Society of America Journal,* 58**,** 653-659.

LINSLER, D., KAISER, M., ANDRUSCHKEWITSCH, R., PIEGHOLDT, C. & LUDWIG, B. 2016. Effects of cover crop growth and decomposition on the distribution of aggregate size fractions and soil microbial carbon dynamics. *Soil Use and Management,* 32**,** 192-199.

LIPIEC, J. & HATANO, R. 2003. Quantification of compaction effects on soil physical properties and crop growth. *Geoderma,* 116**,** 107-136.

LIPIEC, J., MEDVEDEV, V. V., BIRKAS, M., DUMITRU, E., LYNDINA, T. A., ROUSSEVA, S. & FULAJTAR, E. 2003. Effect of soil compaction on root growth and crop yield

in Central and Eastern Europe. *International Agrophysics,* 17**,** 61-69.

LIU, A. G., MA, B. L. & BOMKE, A. A. 2005. Effects of cover crops on soil aggregate stability, total organic carbon, and polysaccharides. *Soil Science Society of America Journal*, 69**,** 2041-2048.

LIU, X., RAHMAN, T., SONG, C., YANG, F., SU, B., CUI, L., BU, W. & YANG, W. 2018. Relationships among light distribution, radiation use efficiency and land equivalent ratio in maize-soybean strip intercropping. *Field Crops Research*, 224**,** 91-101.

LOGSDON, S. D., PARKER, J. C. & RENEAU, R. B. 1987. Root growth as influenced by aggregate size. *Plant and Soil,* 99**,** 267-275.

LONGDEN, P., MAY, M. & FISHER, S. 2002. Weed Beet Control. *British Sugar Beet Review,* 70**,** 38-41.

MALEZIEUX, E., CROZAT, Y., DUPRAZ, C., LAURANS, M., MAKOWSKI, D., OZIER-LAFONTAINE, H., RAPIDEL, B., DE TOURDONNET, S. & VALANTIN-MORISON, M. 2009. Mixing plant species in cropping systems: concepts, tools and models. A review. *Agronomy for Sustainable Development,* 29**,** 43-62.

MALNOU, C. S., JAGGARD, K. W. & SPARKES, D. L. 2006. A canopy approach to nitrogen fertilizer recommendations for the sugar beet crop. *European Journal of Agronomy,* 25**,** 254-263.

MALNOU, C. S., JAGGARD, K. W. & SPARKES, D. L. 2008. Nitrogen fertilizer and the efficiency of the sugar beet crop in late summer. *European Journal of Agronomy,* 28**,** 47-56.

MARTINS, M. D., CORA, J. E., JORGE, R. F. & MARCELO, A. V. 2009. Crop type influences soil aggregation and organic matter under no-tillage. *Soil & Tillage Research,* 104**,** 22-29.

MCKENZIE, B. M. & DEXTER, A. R. 1988. Radial pressures generated by the earthworm aporrectodea-rosea. *Biology and Fertility of Soils,* 5**,** 328-332.

MENCH, M., MOREL, J. L. & GUCKERT, A. 1987. Metal-binding properties of high-molecular-weight soluble exudates from maize (Zea-mays-l) roots. *Biology and Fertility of Soils,* 3**,** 165-169.

MILFORD, G. F. J. 1973. Growth and development of storage root of sugar-beet. *Annals of Applied Biology,* 75**,** 427-&.

MILFORD, G. F. J., BISCOE, P. V., JAGGARD, K. W., SCOTT, R. K. & DRAYCOTT, A. P. 1980. Physiological potential for increasing yields of sugar beet. London: Pitman Publishing.

MILFORD, G. F. J., POCOCK, T. O., JAGGARD, K. W., BISCOE, P. V., ARMSTRONG, M. J., LAST, P. J. & GOODMAN, P. J. 1985a. An analysis of leaf growth in sugar-beet .4. The expansion of the leaf canopy in relation to temperature and nitrogen. *Annals of Applied Biology,* 107**,** 335-347.

MILFORD, G. F. J., POCOCK, T. O. & RILEY, J. 1985b. An analysis of leaf growth in sugar-beet .1. Leaf appearance and expansion in relation to temperature under controlled conditions. *Annals of Applied Biology,* 106**,** 163-172.

MILFORD, G. F. J., POCOCK, T. O. & RILEY, J. 1985c. An analysis of leaf growth in sugar-beet .2. Leaf appearance in field crops. *Annals of Applied Biology,* 106**,** 173-185.

MILFORD, G. F. J., POCOCK, T. O., RILEY, J. & MESSEM, A. B. 1985d. An analysis of leaf growth in sugar-beet .3. Leaf expansion in field crops. *Annals of Applied Biology,* 106**,** 187-203.

MILFORD, G. F. J., TRAVIS, K. Z., POCOCK, T. O., JAGGARD, K. W. & DAY, W. 1988. Growth and dry-matter partitioning in sugar-beet. *Journal of Agricultural Science,* 110**,** 301-308.

MINASNY, B. & MCBRATNEY, A. B. 2018. Limited effect of organic matter on soil available water capacity. *European Journal of Soil Science*, 69**,** 39-47.

MISRA, R. K., DEXTER, A. R. & ALSTON, A. M. 1986. Maximum axial and radial growth pressures of plant-roots. *Plant and Soil,* 95**,** 315-326.

MONROE, C. D. & KLADIVKO, E. J. 1987. Aggregate stability of a silt loam soil as affected by roots of corn, soybeans and wheat. *Communications in Soil Science and Plant Analysis,* 18**,** 1077-1087.

MONTEITH, J. L. 1986. How do crops manipulate water-supply and demand. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences,* 316**,** 245-259.

MOREL, J. L., HABIB, L., PLANTUREUX, S. & GUCKERT, A. 1991. Influence of maize root mucilage on soil aggregate stability. *Plant and Soil,* 136**,** 111-119.

MOREL, J. L., MENCH, M. & GUCKERT, A. 1986. Measurement of Pb-2+,Cu-2+ and Cd-2+ binding with mucilage exudates from maize (Zea-mays-l) roots. *Biology and Fertility of Soils,* 2**,** 29-34.

MORRIS, N. L., MILLER, P. C. H., ORSON, J. H. & FROUD-WILLIAMS, R. J. 2007. Soil disturbed using a strip tillage implement on a range of soil types and the effects on sugar beet establishment. *Soil Use and Management,* 23**,** 428-436.

MORRIS, N. L., MILLER, P. C. H., ORSON, J. H. & FROUD-WILLIAMS, R. J. 2009. The effect of wheat straw residue on the emergence and early growth of sugar beet (Beta vulgaris) and oilseed rape (Brassica napus). *European Journal of Agronomy,* 30**,** 151-162.

MURRAY, G., SWENSEN, J. B. & GALLIAN, J. J. 1993. Emergence of sugar-beet seedlings at low soil-temperature following seed soaking and priming. *Hortscience,* 28**,** 31-32.

MURUNGU, F. S., NYAMUGAFATA, P., CHIDUZA, C., CLARK, L. J. & WHALLEY, W. R. 2003. Effects of seed priming, aggregate size and soil matric potential on emergence of cotton (Gossypium hirsutum L.) and maize (Zea mays L.). *Soil & Tillage Research,* 74**,** 161-168.

NORTON, L. D., MAMEDOV, A. I., HUANG, C. H. & LEVY, G. J. 2006. Soil aggregate stability as affected by long-term tillage and clay mineralogy. *In:* HORN, R., FLEIGE, H., PETH, S. & PENG, X. H. (eds.) *Soil Management for Sustainability.* Reiskirchen: Catena Verlag.

OBER, E. S., LE BLOA, M., CLARK, C. J. A., ROYAL, A., JAGGARD, K. W. & PIDGEON, J. D. 2005. Evaluation of physiological traits as indirect selection criteria for drought tolerance in sugar beet. *Field Crops Research,* 91**,** 231-249.

OBER, E. S. & RAJABI, A. 2010. Abiotic Stress in Sugar Beet. *Sugar Tech,* 12**,** 294-298.

OHNO, T., DOOLAN, K., ZIBILSKE, L. M., LIEBMAN, M., GALLANDT, E. R. & BERUBE, C. 2000. Phytotoxic effects of red clover amended soils on wild mustard seedling growth. *Agriculture Ecosystems & Environment,* 78**,** 187-192.

OKOM, S., RUSSELL, A., CHAUDHARY, A. J., SCRIMSHAW, M. D. & FRANCIS, R. A. 2017. Impacts of projected precipitation changes on sugar beet yield in eastern England. *Meteorological Applications,* 24**,** 52-61.

OLEGHE, E., NAVEED, M., BAGGS, E. M. & HALLETT, P. D. 2017. Plant exudates improve the mechanical conditions for root penetration through compacted soils. *Plant and Soil,* 421**,** 19-30.

OLESEN, J. E. & MUNKHOLM, L. J. 2007. Subsoil loosening in a crop rotation for organic farming eliminated plough pan with mixed effects on crop yield. *Soil & Tillage Research,* 94**,** 376-385.

OSIPITAN, O. A., DILLE, J. A., ASSEFA, Y. & KNEZEVIC, S. Z. 2018. Cover crop for early season weed suppression in crops: systematic review and meta-analysis. *Agronomy Journal,* 110**,** 2211-2221.

PALM, C., BLANCO-CANQUI, H., DECLERCK, F., GATERE, L. & GRACE, P. 2014. Conservation agriculture and ecosystem services: An overview. *Agriculture Ecosystems & Environment*, 187**,** 87-105.

PARKINSON, R. J. 2003. Soil management and crop nutrition. *In:* SOFFE, R. (ed.) *The Agricultural Notebook.* Oxford: Blackwell Science Ltd.

PATTERSON, D. E., CHAMEN, W. C. T. & RICHARDSON, C. D. 1980. Long-term experiments with tillage systems to improve the economy of cultivations for cereals. *Journal of Agricultural Engineering Research,* 25**,** 1-35.

PEIGNÉ, J., CANNAVACUOLO, M., GAUTRONNEAU, Y., AVELINE, A., GITEAU, J. L. & CLUZEAU, D. 2009. Earthworm populations under different tillage systems in organic farming. *Soil and Tillage Research,* 104**,** 207-214.

PENG, X. H., HORN, R., ZHANG, B. & ZHAO, Q. G. 2004. Mechanisms of soil vulnerability to compaction of homogenized and recompacted Ultisols. *Soil & Tillage Research,* 76**,** 125-137.

PERRY, D. A. 1973. Studies on field establishment of monogerm sugar-beet. *Journal of Agricultural Science,* 81**,** 245-252.

PIEARCE, T. G. 1978. Gut contents of some lumbricid earthworms. *Pedobiologia,* 18**,** 153-157.

POCOCK, T. O., MILFORD, G. F. J. & ARMSTRONG, M. J. 1990. Storage root quality in sugarbeet in relation to nitrogen uptake. *The Journal of Agricultural Science,* 115**,** 355-362.

RASBAND, W. S. 2011. ImageJ, U.S. National Institutes of Health, Bethesda, Maryland, USA. *http://imagej.nih.gov/ij/*.

REIJNEVELD, A., VAN WENSEM, J. & OENEMA, O. 2009. Soil organic carbon contents of agricultural land in the Netherlands between 1984 and 2004. *Geoderma,* 152**,** 231-238.

RICHARD, G., BOIFFIN, J. & DUVAL, Y. 1995. Direct drilling of sugar-beet (Beta-vulgaris l) into a cover crop - effects on soil physical conditions and crop establishment. *Soil & Tillage Research,* 34**,** 169-185.

RICHARDS, I. R., WALLACE, P. A. & TURNER, I. D. S. 1996. A comparison of six cover crop types in terms of nitrogen uptake and effect on response to nitrogen by a subsequent spring barley crop. *Journal of Agricultural Science,* 127**,** 441-449.

RICHTER, G. M., QI, A., SEMENOV, M. A. & JAGGARD, K. W. 2006. Modelling the variability of UK sugar beet yields under climate change and husbandry adaptations. *Soil Use and Management,* 22**,** 39-47.

ROLDAN, A., CARAVACA, F., HERNANDEZ, M. T., GARCIA, C., SANCHEZ-BRITO, C., VELASQUEZ, M. & TISCARENO, M. 2003. No-tillage, crop residue additions, and legume cover cropping effects on soil quality characteristics under maize in Patzcuaro watershed (Mexico). *Soil & Tillage Research,* 72**,** 65-73.

ROMANECKAS, K., PILIPAVICIUS, V. & SARAUSKIS, E. 2010. Impact of seedbed density on sugar beet (Beta vulgaris L.) seed germination, yield and quality of roots. *Journal of Food Agriculture & Environment,* 8**,** 599-601.

RPA 2018. Basic Payment Scheme: rules for 2018. *In:* DEFRA (ed.). London: Rural Payments Agency.

RUIZ, S., OR, D. & SCHYMANSKI, S. J. 2015. Soil penetration by earthworms and plant roots—mechanical energetics of bioturbation of compacted soils. *PLOS ONE,* 10**,** e0128914.

SAXTON, K. E. & RAWLS, W. J. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society of America Journal,* 70**,** 1569-1578.

SCHJØNNING, P. & RASMUSSEN, K. J. 1989. Long-term reduced cultivation. I. Soil strength and stability. *Soil and Tillage Research,* 15**,** 79-90.

SCOTT, K. & JAGGARD, K. 1978. How crop grows - seed to sugar. *British Sugar Beet Review,* 46**,** 19-22.

SCOTT, R. K., ENGLISH, S. D., WOOD, D. W. & UNSWORTH, M. H. 1973. The yield of sugar beet in relation to weather and length of growing season. *Journal of Agricultural Science,* 81**,** 339-347.

SCOTT, R. K. & JAGGARD, K. 1993a. Crop physiology and agronomy. *In:* COOKE, D. A. & SCOTT, R. K. (eds.) *The Sugar Beet Crop: Science into practice.* London: Chapman and Hall.

SCOTT, R. K. & JAGGARD, K. W. 1993b. Crop physiology and agronomy. *In:* COOKE, D. A. & SCOTT, R. K. (eds.) *The sugar beet crop.* London: Chapman & Hall.

SHANAHAN, P. W., BINLEY, A., WHALLEY, W. R. & WATTS, C. W. 2015. The use of electromagnetic induction to monitor changes in soil moisture profiles beneath different wheat genotypes. *Soil Science Society of America Journal,* 79**,** 459-466.

SHARRATT, B. S., REICOSKY, D. C., IDSO, S. B. & BAKER, D. G. 1983. Relationships between leaf water potential, canopy temperature, and evapo-transpiration in irrigated and non-irrigated alfalfa. *Agronomy Journal,* 75**,** 891-894.

SHAVRUKOV, Y., KURISHBAYEV, A., JATAYEV, S., SHVIDCHENKO, V., ZOTOVA, L., KOEKEMOER, F., DE GROOT, S., SOOLE, K. & LANGRIDGE, P. 2017. Early flowering as a drought escape mechanism in plants: how can it aid wheat production? *Frontiers in Plant Science,* 8**,** 8.

SHAW, B., THOMAS, T. H. & COOKE, D. T. 2002. Responses of sugar beet (Beta vulgaris L.) to drought and nutrient deficiency stress. *Plant Growth Regulation,* 37**,** 77-83.

SHEN, J., YUAN, L., ZHANG, J., LI, H., BAI, Z., CHEN, X., ZHANG, W. & ZHANG, F. 2011. Phosphorus Dynamics: From Soil to Plant. *Plant Physiology,* 156**,** 997-1005.

SHEPHERD, M. A. 1999. The effectiveness of cover crops during eight years of a UK sandland rotation. *Soil Use and Management,* 15**,** 41-48.

SIEVERS, T. & COOK, R. L. 2018. Aboveground and root decomposition of cereal rye and hairy vetch cover crops. *Soil Science Society of America Journal,* 82**,** 147-155.

SINCLAIR, T. R., TANNER, C. B. & BENNETT, J. M. 1984. Water-use efficiency in crop production. *BioScience,* 34**,** 36-40.

SMIT, A. L. 1983. Influence of external factors on growth and development of sugar beet. Wageningen: Wageningen University.

SOLTANGHEISI, A., RODRIGUES, M., COELHO, M. J. A., GASPERINI, A. M., SARTOR, L. R. & PAVINATO, P. S. 2018. Changes in soil phosphorus lability promoted by phosphate sources and cover crops. *Soil & Tillage Research,* 179**,** 20-28.

STROUD, J. L., IRONS, D. E., WATTS, C. W., STORKEY, J., MORRIS, N. L., STOBART, R. M., FIELDING, H. A. & WHITMORE, A. P. 2017. Cover cropping with oilseed radish (Raphanus sativus) alone does not enhance deep burrowing earthworm (Lumbricus terrestris) midden counts. *Soil & Tillage Research,* 165**,** 11-15.

SWEENEY, R. A. & REXROAD, P. R. 1987. Comparison of leco-fp-228 nitrogen determinator with aoac copper catalyst kjeldahl method for crude protein. *Journal of the Association of Official Analytical Chemists,* 70**,** 1028-1030.

THORUP-KRISTENSEN, K. 2001. Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured? *Plant and Soil,* 230**,** 185-195.

TOWNSEND, T. J., RAMSDEN, S. J. & WILSON, P. 2016. How do we cultivate in England? Tillage practices in crop production systems. *Soil Use and Management,* 32**,** 106-117.

TSIALTAS, J. T. & MASLARIS, N. 2005. Effect of N fertilization rate on sugar yield and non-sugar impurities of sugar beets (Beta vulgaris) grown under Mediterranean conditions. *Journal of Agronomy and Crop Science,* 191**,** 330-339.

UTOMO, W. H. & DEXTER, A. R. 1981. Soil Friability. *European Journal of Soil Science,* 32**,** 203-213.

VALKAMA, E., LEMOLA, R., KANKANEN, H. & TURTOLA, E. 2015. Meta-analysis of the effects of undersown catch crops on nitrogen leaching loss and grain yields in the Nordic countries. *Agriculture Ecosystems & Environment,* 203**,** 93-101.

VAN DAM, A. M. & LANTINGA, E. A. 1998. Leaf CO2 assimilation and leaf dynamics in catch crops during autumn and winter at two levels of nitrogen supply. *Netherlands Journal of Agricultural Science,* 46**,** 249-265.

VAN GROENIGEN, J. W., LUBBERS, I. M., VOS, H. M. J., BROWN, G. G., DE DEYN, G. B. & VAN GROENIGEN, K. J. 2014. Earthworms increase plant production: a meta-analysis. *Scientific Reports,* 4**,** 7.

VOS, J. & VAN DER PUTTEN, P. E. L. 2001. Field observations on nitrogen catch crops. III. Transfer of nitrogen to the succeeding main crop. *Plant and Soil,* 236**,** 263-273.

VOS, J., VAN DER PUTTEN, P. E. L., HUSSEIN, M. H., VAN DAM, A. M. & LEFFELAAR, P. A. 1998. Field observations on nitrogen catch crops - II. Root length and root length distribution in relation to species and nitrogen supply. *Plant and Soil*, 201**,** 149-155.

WAGGER, M. G., CABRERA, M. L. & RANELLS, N. N. 1998. Nitrogen and carbon cycling in relation to cover crop residue quality. *Journal of Soil and Water Conservation,* 53**,** 214-218.

WAGNER, S., CATTLE, S. R. & SCHOLTEN, T. 2007. Soil-aggregate formation as influenced by clay content and organic-matter amendment. *Journal of Plant Nutrition and Soil Science,* 170**,** 173-180.

WAKINDIKI, I. I. C. & BEN-HUR, M. 2002. Soil mineralogy and texture effects on crust micromorphology, infiltration, and erosion. *Soil Science Society of America Journal,* 66**,** 897-905.

WANG, E. H., CRUSE, R. M., CHEN, X. W. & DAIGH, A. 2012. Effects of moisture condition and freeze/thaw cycles on surface soil aggregate size distribution and stability. *Canadian Journal of Soil Science,* 92**,** 529-536.

WEAVER, J. E. 1926. *Root development of field crops,* New York & London, McGraw-Hill Book Company, Inc.

WERKER, A. R., JAGGARD, K. W. & ALLISON, M. F. 1999. Modelling partitioning between structure and storage in sugar beet: Effects of drought and soil nitrogen. *Plant and Soil,* 207**,** 97-106.

WHALLEY, W. R., BINLEY, A., WATTS, C. W., SHANAHAN, P., DODD, I. C., OBER, E. S., ASHTON, R. W., WEBSTER, C. P., WHITE, R. P. & HAWKESFORD, M. J. 2017. Methods to estimate changes in soil water for phenotyping root activity in the field. *Plant and Soil,* 415**,** 407-422.

WHALLEY, W. R., RISELEY, B., LEEDS-HARRISON, P. B., BIRD, N. R. A., LEECH, P. K. & ADDERLEY, W. P. 2005. Structural differences between bulk and rhizosphere soil. *European Journal of Soil Science,* 56**,** 353-360.

WHITELEY, G. M. 1989. The deformation of soil by penetrometers and root-tips of Pisum-sativum. *Plant and Soil,* 117**,** 201-205.

WILLEMS, A. B., AUGUSTENBORG, C. A., HEPP, S., LANIGAN, G., HOCHSTRASSER, T., KAMMANN, C. & MÜLLER, C. 2011. Carbon dioxide emissions from spring ploughing of grassland in Ireland. *Agriculture, Ecosystems & Environment,* 144**,** 347-351.

WILLIAMS, J. D. & WUEST, S. B. 2011. Tillage and no-tillage conservation effectiveness in the intermediate precipitation zone of the inland Pacific Northwest, United States. *Journal of Soil and Water Conservation,* 66**,** 242-249.

WOOD, D. W. & SCOTT, R. K. 1975. Sowing sugar-beet in autumn in England. *Journal of Agricultural Science,* 84**,** 97-108.

WRIGHT, A. J. D., BUSSELL, J. S., STEVENS, M., BACK, M. A. & SPARKES, D. L. 2018. Physiological differences between sugar beet varieties susceptible, tolerant or resistant to the beet cyst nematode, Heterodera schachtii (Schmidt) under uninfested conditions. *European Journal of Agronomy,* 98**,** 37-45.

WUEST, S. B. 2001. Soil biopore estimation: effects of tillage, nitrogen, and photographic resolution. *Soil & Tillage Research,* 62**,** 111-116.

WUEST, S. B. 2009. How Tillage Affects Water Infiltration - Technical notes. *In:* AGRICULTURE, U. D. O. (ed.). Portland, Oregan: USDA.

WYLAND, L. J., JACKSON, L. E. & SCHULBACH, K. F. 1995. Soil-plant nitrogen dynamics following incorporation of a mature rye cover crop in a lettuce production system. *Journal of Agricultural Science,* 124**,** 17-25.

YUNUSA, I. A. M. & NEWTON, P. J. 2003. Plants for amelioration of subsoil constraints and hydrological control: the primer-plant concept. *Plant and Soil,* 257**,** 261-281.

ZINNGREBE, Y., PE'ER, G., SCHUELER, S., SCHMITT, J., SCHMIDT, J. & LAKNER, S. 2017. The EU's ecological focus areas – How experts explain farmers' choices in Germany. *Land Use Policy,* 65**,** 93-108.