April 2020

Project Report No. 620

Maxi Cover Crop:

Maximising the benefits from cover crops through species selection and crop management

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This is the final report of a 38-month project (21140009) that started in August 2016. The work was funded by Amazone Ltd, Cousins of Emneth Ltd, Hutchinsons, RAGT seeds and a contract for £230,000 from AHDB.

CONTENTS

1. Abstract

In a recent survey of UK farmers, the most cited reasons for not growing cover crops were: (i) they did not fit with the current rotation (ii) expense and (iii) difficulty of measuring their benefit to crop production. The Maxi Cover Crop project aimed to address some of these issues by characterising the performance of a range of cover crop species, both individually and in mixes of increasing complexity, under field conditions, and by performing a cost/benefit analysis on the systems used. The project has measured, assessed and quantified the impacts of the cover crops on soil properties and the performance of the subsequent two crops in the rotation. It has also provided new data on the depth of rooting and root density from different cover crop species and mixes, and developed a template for growers to perform a cost/benefit analysis of using cover crops in their rotations. A key feature of the work has been the use of tramline trials on commercial farms to complement the work undertaken on the more traditional field experimental plots. These sites provided more data from field scale comparisons carried out in commercial farming systems on a wider range of soil types.

The results have confirmed that early establishment (August rather than September) is important to maximise the benefits of cover crops, particularly to ensure good crop cover and nutrient recovery. Above-ground, radish, buckwheat and a mix comprising radish, buckwheat and phacelia were quickest to establish. However, below ground, it was the rye cover crop that produced the greatest amount of roots, both early in the season and at destruction (average root length density or RLD, of 3.5 cm root/cm^3 soil to 60cm depth, compared to a RLD of 1.2 cm/cm^3 from the volunteers/weeds on the control treatment; note root assessments excluded the tap root); rye also had the widest root diameter (at *c.* 0.23 mm). Phacelia roots were slower to develop, but by destruction had a high RLD (3.4 cm root/cm^3 soil), particularly in the topsoil, and also produced the narrowest roots (*c.* 0.19 mm). It also had a high specific root length, or SRL, (length of root in metres per unit of root biomass in grams, at 268 m/g), suggesting it explored more of the soil for a given root biomass compared to the other cover crop treatments (e.g. vetch at 188 m/g). A high SRL is considered to be important for soil structural improvement, although there was little evidence of changes in soil properties following the different cover crop treatments at the large plot experimental sites, and no relationship observed between cover crop rooting and spring crop rooting. However, there was some evidence of soil improvement (lower penetration resistance, lower bulk density and improved visual structural score) following a single year of growing a cover crop mixture at two of the tramline trial sites on medium textured soils; earthworm numbers were also increased where a five species mix had been grown (the other two tramline trial sites were on heavy textured soils).

On average, the different cover crops took up between 30 and 50kg N/ha, although up to 90kg N/ha was recovered by the vetch and clover cover crops following early establishment at one of the sites (medium-textured soil type). Highest N recovery was associated with either species that were able to fix additional N (i.e. clover and vetch) or established good above- or below-ground biomass, early in the season (radish, phacelia and rye). The N uptake by the cover crop treatments was not detected in the spring barley crop or soil at harvest; the fate of cover crop N remains a key research question.

It was clear from both the large plot and tramline trials that cover cropping on heavy textured soils can result in increased topsoil moisture, probably due to the crop cover preventing surface evaporation. In these circumstances and depending on the weather, late destruction (late March/early April) and incorporation of a high cover crop biomass (less than one week prior to drilling the cash crop) can result in a poor seedbed for subsequent cash crop establishment, leading to lower crop yields.

There was also clear evidence of a negative impact of growing a cereal cover crop (oats and particularly rye) on the subsequent performance of the spring barley crop, in terms of rate of crop establishment, rooting to depth and ultimately grain yield, providing robust evidence that cereal cover crops (as a single species) should not be grown ahead of a spring cereal cash crop. The reason for this is uncertain, but N immobilisation or pest and pathogen carry-over ('green bridge') have been cited as possible causes. Whether this can be negated by using the cereal cover crop in a mix or how much of the mix can be cereal is unclear. However, cash crop yields in the replicated plot experiments were not reduced following cover crop mixes comprising between 55 and 83% spring oat. None of the trialled mixes included rye. These results have implications for the CAP EFA greening rules (BPS 2020), which require cover crop mixes to include a cereal and non-cereal. However, although the results suggest cereal cover crops should be part of a mix rather than grown as a straight (when followed by a spring cereal cash crop), there was no clear evidence that the performance of the other cover crop species (notably radish and phacelia) was improved by inclusion within a mix. Indeed, the highest cumulative margin was achieved by growing oil radish as a monoculture, rather than within a mix.

There was a trend for a higher spring barley grain phosphorus (P) concentration and grain P offtake where buckwheat had been grown compared to the control treatment (volunteer/weeds). This additional evidence corroborates that reported in the literature. However, the mechanism for increasing the solubility of soil P is uncertain, as rooting by the buckwheat and total above ground biomass production was low compared to the other species evaluated.

Cumulative (two-year) margins were calculated for all of the seven study sites (20 comparisons), with most (95%) showing a reduction in margin compared to no cover crops (ranging from + £64/ha following oil radish on a clay loam to - £476/ha following a two species mix on a clay soil; average of - £150/ha), due to the absence of a sufficient yield benefit to compensate for the additional seed and establishment costs. There was also no evidence that soil type influenced the economic performance of cover crops. However, the greatest reductions in margins were where cover crops resulted in a significant yield reduction as a result of poorer establishment conditions, which tended to be on the heavier soil types.

As well as providing robust scientific evidence of the physiology and performance of a range of cover crop species, Maxi Cover Crop has provided useful insights into the practicality of using cover crops across a range of soil and climatic conditions. The involvement of commercial farmers in trialling some of the mixtures and methodologies of crop establishment has been particularly valuable, with some farmers changing practices as a result of their involvement in the work.

2. Introduction

There is an increasing need to manage soils sustainably, and both UK farmers and the UK government recognise the importance of soil for providing food and delivering other benefits such as bio-diversity, clean air and water, flood regulation and carbon storage (Defra, 2009, 2018). Cover crops are grown primarily for the purpose of 'protecting or improving' between periods of regular crop production and can contribute to sustainable crop production through several mechanisms including; increasing soil nutrient and water retention, improving soil structure/quality, reducing the risk of soil erosion, surface run-off and diffuse pollution by providing soil cover and by managing weeds or soil-borne pests. They can also count towards Common Agricultural Policy (CAP) greening requirements as part of an 'Ecological Focus Area' or EFA, and are likely to be a feature of the future Environmental Land Management schemes (ELMs) being introduced as part of the Agriculture Bill (https://commonslibrary.parliament.uk/research-briefings/cbp-8702/), where farmers will be paid to produce 'public goods'. This draws on evidence from the 25 year plan for the Environment (Defra, 2018) where cover crops were clearly identified as a potential means of improving soil health.

However, there are also potential undesirable effects of cover cropping, which may reduce farm productivity e.g. rotational conflicts, increased weed pressure and increased costs. For the benefits to be fully realised, understanding the impact that different cover crop species have on soils and the following crops in the rotation is critical so that farmers can decide the most appropriate species and management for their rotation. Currently, the benefits of cover crops are often not realised because of a lack of evidence about the impact that different cover crop species have on contrasting soil types and rotations. A recent survey of UK farmers, found that the most common reasons farmers did not grow cover crops were (i) they did not fit with the current rotation, (ii) expense and (iii) the difficulty of measuring their benefit (Storr et al. 2019). Understanding the effects of different cover crops on soil properties, yield and other services that soils provide is essential to realise the potential benefits. There is a need for practical science-based information on cover crop selection and management in UK conditions to provide improved guidance on the effective use of cover crops in UK arable systems.

2.1. Objectives

This project ('Maxi Cover Crop') aimed to maximise the potential economic, agronomic and ecological benefits from cover crops through a better understanding of species effects and crop management approaches.

The specific objectives were to:

1) Quantify the effects of different cover crops on soil properties, crop rooting and yield; *this was achieved using three field experiments (section 3).*
2) Validate the effects of different cover crop mixtures and cultivation approaches on AHDB Monitor Farms; *this was achieved using four tramline trials evaluating two cover crop mixes ('cover crop validation tramline trials'; section 4) and four trials evaluating three different cover crop establishment methods ('cultivation validation tramline trials'; section 5).*
3) Enable AHDB to update cover crops guidance.
4) Transfer knowledge of the project findings to growers, industry and academia.

2.2. Literature Review Update

This section aims to provide a brief and focused update on the literature, including peer reviewed journals, project reports and results and press releases since the publication of AHDB research review No. 90 (White et al. 2016). The focus is on work conducted in the UK (although not exclusively so) and on topics relevant to those examined in the Maxi Cover Crop project.

2.2.1. Potential benefits of cover crops

The benefit of cover crops for soils and crops, whether due to increased nutrient and water retention, improved soil structure/quality or reduced erosion continue to be a focus of much of the scientific literature on cover cropping since AHDB review No. 90. However, findings on-farm tend to be mixed, with a recent survey of 117 farmers in the UK indicating uncertainty regarding the effect of growing cover crops on soil organic matter content and nutrient availability. The survey reported more positive findings for their effect on soil structure, earthworm numbers and erosion control, particularly where cover crops had been used for more than three years (Storr et al., 2019).

Effect of cover crops on soil quality

It is clear from the literature that cover crops, particularly when grown for a number of successive years, can result in improvements in soil physical (e.g. structure and aggregate stability), chemical (e.g. organic carbon and nitrogen) and biological (e.g. earthworm populations and microbial biomass) properties (Abdalla et al. 2019; Restovich et al. 2019; Shackelford et al. 2019). For example, Shackelford et al. (2019) calculated 'response ratios' in order to understand the impact of having a cover crop on a number of soil properties in a meta-analysis of 57 publications, covering 326 experiments on arable farmland in California and the Mediterranean. Soils following cover cropping were seen to have 9% more organic matter, 41% more microbial biomass and 13% less water, compared to bare soils or winter fallows. Likewise, Restovich et al. (2019), following a six year study of the effects of cover crops in a maize rotation, reported increases in soil porosity (the proportion of macropores in the 60-300μm size class increased from 5 to 9%), aggregate stability (stability at 0-5cm depth increased from 25 to 43%) and topsoil organic carbon (average increase of 0.36 ± 0.26 t/ha/yr), with a vetch cover crop also increasing topsoil organic nitrogen (by *c.* 0.5 t/ha over the 6 year period in the absence of N fertiliser). Field experiments in the UK testing the effects of cover crops ahead of vining peas, found that on heavier land, compaction was highest in the uncovered control treatment (Jelden and Herold 2019). For soil biology, Crotty & Stoate (2019) found no difference in total earthworm numbers following 3 different cover crop mixes on a heavy clay soil in Leicestershire, but significant differences in the number of litter dwelling earthworms (epigeic worms) following a 3 or 4 species mix compared to no cover or a two species cover crop mix. Moreover, a survey of earthworm numbers from 126 fields showed that that cover cropping significantly increased the presence of anecic (deep burrowing) earthworms (Stroud 2019).

However, the benefits of cover crops to soil quality have been seen to be strongly dependent on climate, soil type and species grown (ORC 2016). For example, growers have reported erosion control by cover crops to be greater on light land compared to heavy land (Storr et al. 2019). In the case of soil moisture, in wet winters the removal of excess water via cover crop growth can be beneficial, however, in dry years removal of water from the soil by the cover crop may reduce available water supply for the following crop (Storr et al. 2019). Moreover, the use of cover crops does not always support increased populations of earthworms (Roarty et al. 2017; Stroud et al. 2017). For example, after a three year cover crop and spring barley rotation in Ireland there was some evidence that pea and oat cover crops supported larger and more species rich populations of earthworms compared to where there was no overwinter vegetation. However, the study also showed that brassica cover crops, such as mustard did not support larger earthworm populations

(Roarty et al. 2017). Mustard species are also reported in the literature as having little benefit to soil structure (Hallama et al. 2018).

The benefits of cover crops, particularly in terms of physical and chemical processes have been thoroughly investigated in recent years (Munkholm and Hansen, 2012; Bronick and Lal, 2005 and Cooper *et al*., 2017). However, few studies have investigated the impact on soil biology, which play a key role in soil nutrient cycling and soil organic matter breakdown. To address this a recent study financed as a BBSRC Industrial Case PhD studentship with the John Innes Centre and Syngenta as partners, aims to investigate the role of cover crops, companion cropping and herbal leys in several long-term field trials on soil health from an ecological perspective. Initial findings show that growing a brassica cover crop (radish, *Raphinus sativus*) caused a reduction below-ground diversity shown by changes to the structural composition of the communities (Figure 2-1; M. Fioratti, pers. comm.). This work is on-going, with future publications expected towards the end of the research project in 2021. Another recently initiated research project (2018 – 2021), funded by BBSRC and being conducted by T. Sizmur of Reading University is also looking at how the incorporation of a mixture of biochemically diverse crop residues in the form of cover crop green manure mixtures affect the structure of the soil microbial community, nutrient use efficiency and crop yields (https://gtr.ukri.org/projects?ref=BB%2FR006989%2F1).

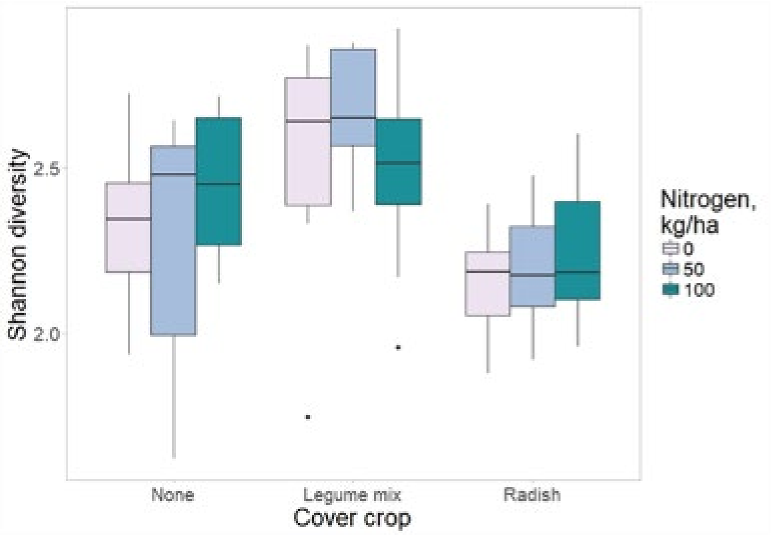


Figure 2-1 Soil biodiversity (springtails, beetles and mites) in the NFS Rotations study following three cover crop treatments (legume mix, radish and a bare fallow control) and three nitrogen application levels (0, 50 and 100% of the recommended dose). Plots were sampled in the 2018 spring barley crop following the winter cover crop treatments, with 4 previous iterations of cover crops being grown in 2009, 2011, 2013 and 2016. (Image courtesy of M. Fioratti)

Effect of cover crops on nitrogen and phosphorus cycling

There has been an increasing amount of work conducted by UK water companies and levy bodies investigating and demonstrating the effect of cover crops on water quality across a range of soil types:

- Wessex Water (Martin, 2018 a,b) have conducted several trials in Dorset over winters 2016-17 and 2017-18 exploring the impact of drilling date and cover crop species on nitrate leaching before maize establishment. Trials were undertaken in response to concerns about the use of cover crops following late harvested crops (due to establishment problems) as well as the use of brassica cover crops (due to conflicts with oilseed rape rotations, early drilling dates and their susceptibility to damage by slugs and cabbage stem flea beetle). In 2016-17, 4 drilling dates were tested (late August, early and late September and late October); nitrate leaching was reduced to negligible levels (< 5 kg/ha compared to 42 kg/ha on the control) by all of the early sown treatments (August and early September), with some reduction (0-35%) following the late September drillings (here oil radish was the most effective). Nitrate leaching losses increased following the October drilling date, reflecting the disturbance (and N mineralisation) caused by drilling. Early sown brassicas were the most effective at reducing nitrate leaching losses taking up between 25 and 70 kg N/ha. In 2017-18, 16 different cover crop treatments were evaluated on two drilling dates, with leaching measured from 3 of the treatments (oil radish, Italian ryegrass, oats/phacelia mix). All cover crop treatments reduced nitrate leaching, although the earlier drilled (late August) treatments were more effective (*c*. 90% reduction) than the late drilled (late September) treatments (*c*. 40% reduction); there was virtually no leaching from oil radish sown early, and species such as Italian ryegrass or a mix of oats and phacelia, although slower to establish, were almost as effective (*c.* 80% reduction). Key conclusions from this work were that brassica cover crops are the most effective at taking up nitrogen and reducing nitrate leaching, but other species such as cereals and phacelia are also effective if drilled early.
- Thames Water (Shah et al. 2017) measured nitrate leaching from 3 cover crop treatments (2 mixes and oil radish) compared to an uncovered control at two sites on silty clay loam soils in Gloucestershire (drilled late August into cultivated soil) and Hampshire (direct drilled in early September) over winter 2015-16. Nitrate-N concentrations in the drainage waters were reduced from an average of 40 to less than 15mg/l at the Hampshire site and from 60 mg/l to 20-40 mg/l at the Gloucestershire site; cover crop biomass and N uptake were similar at both sites (*c*. 1.4-1.6 t/ha dry matter and 45-50 kg/ha N uptake).
- Affinity Water (T. Clarke, FWAG, pers. comm.) have funded a series of on-farm, un-replicated demonstrations of the use of cover crops to reduce nitrate leaching in south-east England. Here work has been undertaken for 3 successive winters, with 6 different cover crop species mixes, varying in complexity. All cover crop treatments reduced the nitrate concentration of drainage waters, taking up between 60 and 100 kg N/ha.
- Portsmouth Water (Bhogal, 2019): On-going work as part of an INTERREG CPES funded project with Portsmouth water (2018-2021) aims to demonstrate the feasibility of growing cover crops before the establishment of spring crops to reduce nitrate leaching losses from

the shallow chalk soils found across much of Portsmouth Water's catchment area. The first season's results (2018-19), from un-replicated field-scale plots (tramline widths), provided a clear demonstration of the benefit of growing an oat/phacelia cover crop mix (providing 90% cover and taking up *c.* 50kg N/ha) at reducing the amount of N lost by leaching. Nitrate-N losses were lowest from the oat/phacelia mix at 10kg N/ha compared with 30kg N/ha by the weedy stubble (45% cover) and *c*. 60 kg N/ha from the poorly established oat cover crop (*c.* 30% cover).

- Anglian Water (K.E. Smith, ADAS pers. comm.) carried out a field demonstration (2017/18) investigating the impact of contrasting ground cover on over-winter nitrate-N leaching losses from freely draining soil in the North Lincolnshire Chalk area. Five ground cover treatments were established: 1) stubble (uncultivated), 2) cultivated, 3) oats with mustard, 4) radish with oats, and 5) premium mix (10 different species). All cover crop treatments were drilled on 29 August 2017 and established well. There was a good relationship between percentage ground cover and the amount of nitrate-N lost by leaching. Over-winter nitrate-N leaching losses were highest from the stubble treatment at 90kg N/ha where ground cover was <5%. Nitrate-N leaching losses were lowest at <10kg N/ha on both the radish with oats (80% ground cover) and premium mix (90% ground cover), followed by oats with mustard (60% ground cover) treatment at *c*.25kg N/ha. The demonstration found that a light cultivation stimulated weedy growth, which helped to reduce nitrate leaching losses to c.60kg N/ha (i.e. *c*.30% reduction) compared to leaving in stubble, which had limited weedy growth.
- The green pea company/PGRO (Jelden and Herold 2019) investigated the integration of cover crops in a vining pea rotation and concluded (from measurements of changes in soil mineral N and cover crop N) that nitrate leaching had occurred on the uncovered control treatment but not where cover crops (5 different species mixes) were grown.
- Defra-funded Demonstration Test Catchments Initiative (Cooper et al. 2017) measured the effect of an oilseed radish cover crop established using shallow non-inversion tillage or by direct drilling with a winter ploughed fallow on nitrate leaching losses at a catchment scale (3 'blocks' of fields covering *c*. 143 ha sandy loam-sandy clay loam soils over chalk in Norfolk). The cover crop reduced nitrate leaching losses by 75-97% relative to the fallow block, but had no impact on P losses, with soil nitrate-N concentrations reduced by *c*. 77% at 60-90 cm. The application of starter fertiliser to the cover crop (30kg/ha) in one of the study years increased the cover crop biomass and N uptake (by *c*. 10kg/ha), but also led to increased soil nitrate-N concentrations and higher nitrate concentrations in the drainage waters.
- On-going demonstrations at the AHDB Strategic Farm East have shown a clear benefit of over winter cover on the nitrate concentration of drainage waters from heavy textured soils across the farm. A split field demonstration (bare ploughed soil vs. oil radish/rye cover crop;

with two separate drainage systems) over winter 2018-19 reported nitrate-N concentrations in excess of 50 mg/l from the bare-plough compared to < 5 mg/l from the cover crop treatment (https://ahdb.org.uk/farm-excellence/strategic_cereal_farm_east)

The work listed above is also supported by the scientific literature and provides robust evidence that over-winter cover reduces nitrate leaching losses, with the level of reduction dependant on the species used, drilling date and success of establishment. For example, Abdalla et al. (2019) reviewed 106 studies, covering different countries, climatic zones and management practices and concluded that cover crops including both legumes, non-legumes and mixes of the two, significantly reduced nitrate leaching compared to stubble/bare ground controls. Likewise, Shackelford et al. (2019) reviewed 326 experiments on arable farmland in California and the Mediterranean and reported 53% lower nitrate leaching from non-legume cover crops compared to un-covered controls, however leaching from legume cover crops was similar to the control treatments (P>0.05). Other studies have suggested legume cover crops may be less effective at reducing nitrate leaching. For example Aronsson et al. (2016), measured a 90% decrease in leaching from a ryegrass cover crop on a sandy soil in southern Scandinavia, but a 62% increase in nitrate leaching from a legume (red clover) cover crop on a clay soil in the same region. In a meta-analysis of 28 studies, Thapa et al. (2018) found that N leaching was reduced by 56% with non-legume cover crops compared to bare soils, and that a legume mixed with a non-legume could be just as effective, but not when it was grown on its own. Similarly Vogeler et al. (2019) reported that although a pure stand of a legume cover crop (clover or vetch) was less effective at reducing nitrate leaching compared to a pure stand of perennial ryegrass or fodder radish (28-55% reduction from the legume compared to 51-80% reduction from the non-legume), when combined in a mixture with a non-legume, leaching losses were similar (49-81% reduction) to those of a pure stand of the non-legume cover crop. Evidence from the literature shows that to reduce nitrate leaching the use of non-legume cover crops are preferable and that cover crops should be sown as early as possible to enable good establishment, biomass production and consequently N uptake.

Whilst there is clear evidence that cover cropping (particularly by non-legumes) can reduce nitrate leaching, there is still considerable uncertainty regarding when nitrogen recovered by a cover crop is mineralised and made available for subsequent crops, or whether this N can potentially be lost by leaching in subsequent winters. Moreover, there is also the possibility that incorporation of cover crop residues may result in temporary N immobilisation, which could affect the establishment, N fertiliser requirement and performance of the subsequent cash crop. This uncertainty was recently highlighted by the farmer survey conducted by Storr et al. (2019) who reported a high number of “don’t know” responses to a question about nitrogen immobilisation. Likewise in the United States, cover crops are often not adopted because of lack of knowledge on the synchrony of cover crop N release and the N demand of the following crop (Nevin et al. 2020).

Many studies report only above-ground N uptake, but storage of N in cover crop roots is likely to differ between species and the way their roots decompose may affect subsequent N release (Herrera et al. 2017). In a study investigating the decomposition and nutrient release of hairy vetch and cereal rye, hairy vetch above and below ground biomass decomposed at a faster rate than the rye. The vetch had a higher N content and lower C to N ratio compared to the rye in both the above and below ground biomass (Sievers and Cook 2018). Differences in the C:N ratios were expected to result in differences the rate and pattern of decomposition with the authors suggesting that the initial decomposition of rye residues could potentially lead to N immobilisation. Nevin et al (2020) also compared the effect of rye and vetch cover crop residues, either as a straight or in a mix on the activity of enzymes involved in C (β glucosidase) and N (urease) cycling in a corn/soyabean rotation on a silty loam soil. The activity of β glucosidase (involved in the decomposition of cellulose) was greatest following the rye cover crop, but there was no increase in soil inorganic N content, which the authors attributed to N immobilisation. Hallama et al. (2018) also reported that a rye cover crop can potentially result in the immobilisation of nutrients.

For phosphorus, there is little evidence that cover crops reduce P leaching (Aronsson et al. 2016). The focus of this review has been to identify whether cover crops can be used to 'scavenge' soil P thereby making it more available to the subsequent cash crop, either through increased root exploration (roots and mycorrhizae) or by 'mobilising' P from more recalcitrant soil pools (e.g. organic P). Cover crop biomass and P concentration determine the amount of P cycled through the biomass. Cover crop P uptake reported in a recent meta-analysis typically ranged between 3 to 10 kg P/ha, although uptakes of between 1 and 30kg P/ha have been measured depending on the crop species and soil P availability (Hallama et al. 2018). The root to shoot partitioning of P in cover crops is also variable, with 16 to 65% of the total plant P reported to be in the roots (Hallama et al. 2018). Hallama et al. (2018) found that that cover crops in the Family Poaceae, which includes rye and oat, produced the highest quantities of biomass, but had the lowest mean P tissue concentrations (*c.* 2 g P/kg) with limited effect on the yield of the subsequent cash crop (Hallama et al. 2018). Cover crops of the family Fabaceae, which includes vetches, were the most effective (in terms of impact on the P use by the following cash crop) across all conditions and systems, due to both a high biomass and P concentration.

Buckwheat has been reported in the literature as being a P scavenger and mobilizer (Hallama et al. 2018; Valenzuela and Smith 2002). The roots of buckwheat exude substances which help to solubilise P that may otherwise be unavailable to other plants and have also been found to have a high P storage capacity for inorganic P (Valenzuela and Smith 2002). Therefore, when buckwheat is incorporated into the soil it decays quickly, making P, and other nutrients, available to the succeeding crop (Valenzuela and Smith 2002). For example, in a comparison of spring wheat and buckwheat grown in a silty clay soil, more P was found in available P pools after buckwheat harvest compared to wheat (Teboh and Franzen 2011). Buckwheat took up significantly more P from the inorganic pool compared to wheat, whereas wheat took up significantly more P from the organic pool (Teboh and Franzen 2011). However a meta-analysis did not find increases in yield or plant available P for the following crop from a pure stand of buckwheat, which was suggested may have been due to the low cover crop biomass (Hallama et al. 2018). Possinger et al. (2013) also found that soil P was not affected by buckwheat in both low P status experimental plots and P fertilised plots, although the concentration of the organic anion, tartrate, was significantly higher in the rhizosphere of plants grown in the low P soils, suggesting that organic anion root exudation may be involved in buckwheat P dynamics. Root released organic anions are widely documented as a key physiological strategy to enhance soil P availability (Lambers et al. 2006, 2015, Wang et al. 2016).

Effect of cover crops on cash crop performance

In the survey of UK farmers conducted by Storr et al. (2019), 15% of respondents reported a yield benefit following a cover crop, 2% reported yield declines, while 30% didn't know the effect of cover cropping on yield. Positive, negative and no effects of cover crops on yield have been reported in the literature, and this has been related to multiple factors, including the cover crop species, the following cash crop, climatic conditions and the method and timing of destruction (termination). Interestingly, Hallama et al. (2018) suggested that for conventional high-input systems there is little likelihood of yield improvements, but there is the potential for environmental benefits.

Reviews and meta-analyses on the subject by Shackelford et al. (2019), Abdalla et al. (2019) and Hallama et al. (2018) covering multiple studies from different countries, climatic zones and management practices suggest that the 'best' performance in terms of yield benefit has generally been seen following legume cover crops, or mixes containing legumes. This is the opposite to what has been found from a water quality perspective, which suggests that the 'best' performance (i.e. lowest nitrate leaching) is generally achieved with non-legume cover crops, and highlights the importance of chosing cover crop species/mixes that are best aligned to the desired outcome (see section 2.2.2 below).

Maize has been identified as one of the most responsive crops, with cover crop mixtures more beneficial for maize yields than straight cover crops (Hallama et al. 2018). For example, the review of 326 studies by Shackelford et al. (2019) indicated that cash crop yields were 16% higher following legume cover crops compared to control plots, but yields were 7% lower following non-legume cover crops (however studies were undertaken in California and Mediterranean regions). Abdalla et al. (2019) also found (from a review of 106 studies) that cash crop yields were on average 4% lower following cover crops, except following a mix comprising both legume and non-legume species where yields were increased by *c.*13%, although it was uncertain why this was the case.

Table 2.1 summarises results from recent UK studies investigating the effect of cover crops on cash crop yields. None of the studies reported yield declines and the work by BBRO collating results from a number of on-farm trials (Impey, 2019) indicated that the likelihood of a yield response to cover cropping increased if beet was established with minimum tillage and if the site already had cover crops in the rotation.

Table 2.1 Summary of recent UK studies on the effect of cover crops on cash crop yields

Study reference	Soil type	Cash crop	Cover crop	Yield ‘benefit’
Jelden and Herold, 2019	Light	Pea	4 mixes and one straight (vetch)	Up to 1 t/ha ⥣ (no yield differences on a heavier textured soil)
Wollford and Jarvis, 2017	Heavy	Spring oats	Oat & radish Radish	0.25 t/ha ⥣ 0.75 t/ha ⥣
Mowbray 2019	Light	Spring barley	7 species over 3 consecutive years	0.6 t/ha ⥣ by year 3 (oil radish the best performer)
Impey 2019	Various	Sugar beet	12 mixes	5-10% ⥣

2.2.2. Cover crop agronomy

Species selection

In the survey of UK farmers by Storr et al. (2019), most respondents grew mixtures of 2 – 4 species, with only 18% of respondents growing single species. Pre-packaged mixtures were not the most popular option, with 44% of farmers surveyed producing their own mix and 30% having a custom mix made. These farmers tended to be those who had at least 2 years of cover crop experience, suggesting that with experience farmers preferred to select species that they knew worked well for their own circumstances. Farms on heavier textured soils tended to use a high proportion of radish and oats in their cover crop mix, whereas those on light soils tended to include a clover and phacelia. The use of radish on heavier land was thought to be due to its long taproot, and may be a response to the need to ameliorate compaction (Chen and Weil 2010).

When choosing a cover crop species or mix it is important to understand the purpose of the cover crop (e.g. soil cover/erosion control, nutrient retention, weed suppression, fertility, soil structure, etc). It is important to match the individual attributes of a cover crop species/variety to the intended purpose taking into account how it might interact with other species in the mix and any potential rotational conflicts. A key consideration identified by AHDB research review No. 90 (White et al. 2016) was to characterise and evaluate the performance of different cover crop species and varieties with respect to rooting. 'Bio-drilling' is a term used to describe the creation of 'biopores' by deeply penetrating plant roots that allows the subsequent use of these pores by the roots of succeeding crops by offering low resistance to growth (Cresswell and Kirkegaard, 1995). The use of cover crop rooting to create biopores and act as a 'tillage tool' alongside reduced cultivations, has been suggested as a potential way of alleviating soil compaction and improving soil structure (Burr-Hersey et al. 2017). It is thought that tap-rooted species and species with thick primary roots may exhibit better penetration abilities in compacted soils compared to fibrous rooted species. This reflects the greater resistance to buckling of tap rooted species, which may be more beneficial for use in biological tillage (Cheng and Weil, 2009). However, there have only been a limited number of studies conducted on how cover crops root. The most recent studies are summarised below:

- Bodner et al (2014) and Yu et al. (2016): looked at the relationship between root traits (to 7cm depth) and pore size distribution in field-grown cover crops (10 cover crops and 2 mixes) on a silty loam soil in Northern Austria. Linseed, phacelia and a mixture of vetch, phacelia and mustard had the highest root length densities (RLD = cm root/cm^3 soil) at 11.0, 5.7 and 6.6 cm/cm^3 respectively, while buckwheat (1.8 cm/cm^3) and rye (2.4 cm/cm^3) had the lowest. The low RLD value for rye was attributed to poor establishment and low above ground biomass (< 1 t/ha). In contrast, buckwheat grew well (*c*. 2 t/ha biomass) suggesting this species had a low dry matter allocation to the root system. Soil water infiltration rates were also measured and, using modelling, the authors concluded that species with both high root density (influencing soil aggregate stability), and high root thickness (influencing drainage pores), could potentially make a soil more resistant to runoff and erosion. It was concluded that root axes thickness, expressed by specific root length (length of root per unit of biomass or SRL) or median root radius were important attributes for improving soil structural properties. Legume species such as yellow sweet clover and grass pea, with a high root diameter (>0.4 mm) and low SRL (<100 m/g) were the most beneficial for soil macro-porosity, with linseed (having a high RLD) also considered to be effective. Whereas, species with a high density of fine roots (e.g. phacelia with a root diameter <0.3mm and SRL of 185 m/g) were most beneficial for soil micro-porosity and had a greater effect on soil moisture content (increased drying).
- Wendling et al (2016): measured root and shoot traits of 20 field-grown cover crop species to 50 cm depth in a sandy loam soil in Switzerland. Five groups of cover crop were identified:
    - High root and shoot biomass, but low tissue N concentration and roots with a large diameter and surface area; mustard, sunflower

    - Medium shoot biomass, but high root length density (RLD) and high tissue N concentration; phacelia
    - Intermediate – species presented both high root and shoot biomass and RLD; radish, oats, clover
    - Low nutrient concentration, high root diameter; buckwheat
    - Low RLD, but high specific root length (SRL – length of root per unit of biomass); vetch.
- Herrera et al. (2017): measured rooting in a field rhizotron study (to 1.1m depth), conducted over three years on a sandy loam soil in Switzerland. They found that a yellow mustard cover crop produced the most roots compared to phacelia and sunflower. The mustard roots also had a higher C:N ratio.
- Burr-Hersey et al. (2017): Visualised and quantified how changes in soil bulk density affected the rooting of 3 cover crop species: tillage radish, vetch and black oat, grown in soil columns that had been artificially compacted (comprising an un-compacted sandy loam topsoil over compacted subsoil). Using X-ray computed tomography, they saw 'fanging' by the radish cover crop (i.e. where a single tap root produces multiple perpendicular roots at the point of soil compaction), root diversion by the vetch cover crop (roots diverted horizontally with little penetration into the compacted zone), and no change in rooting properties of the black oat cover crop which had greatest root surface area and proliferation in the compacted zone. Radish had the greatest root volume in the compacted zone, but black oat the greatest root surface area due to the production of multiple thinner roots.

An on-going BBSRC funded project 'Using roots to bio-engineer soil' should provide more UK-relevant results on differences in cover crop rooting (https://www.cranfield.ac.uk/research-projects/using-roots-to-bio-engineer-soil). This project aims to develop a novel framework to select and combine complementary root traits in cover crops that prevent soil resource losses and improve crop growth conditions. Early results suggest that cover crops with large tap roots are not necessarily best at reducing compaction.

Cover crop establishment and destruction

AHDB research review No. 90 (White et al., 2016) discussed the various methods and factors to take into account when establishing cover crops, with the technique employed depending on cover crop species, soil type, site, weather conditions and previous cropping. In most situations following early harvested combinable crops, a cover crop can be drilled or broadcast followed by seedbed consolidation (Stobart 2015). However, recent work by Shepherd's seeds in Lincolnshire, UK, suggested that under the right conditions, broadcasting a cover crop into a standing cereal crop could potentially be a quick and cost-effective way to establish a cover crop (Robinson 2018). The success of this technique will depend on cover crop species, timing (i.e. date) of establishment and soil moisture content. Timing was considered to be critical, as broadcasting too early (> 20-25 days prior to harvest) may result in too large a cover which will cause difficulties with harvesting the standing crop, whereas establishing too late (<10 days prior to harvest) may result in the cover crop being smothered by straw and chaff at harvest. Ideally, the aim would be for the cover crop to reach the height of the stubble (typically 11 cm) by harvest. Of the species tested, mustard and buckwheat were the fastest to reach a height of 11cm at an average of around 20 days, across two experimental sites. Black oats and forage rye were generally slower to reach 11cm tall, taking on average 24 and 23 days, respectively. Soil moisture status was also a key factor, with larger seeded species requiring more moisture to germinate, such that in areas which tend to be drier, it was suggested that direct/conventionally drilling cover crops post-harvest might be a more suitable establishment technique (Robinson 2018).

The most widespread method of destroying cover crops is to use herbicide, mainly glyphosate. In the survey of UK farmers, 81% used a herbicide to terminate the cover crop, with the majority of remaining respondents using some form of cultivation or biomass removal such as mowing or grazing (Storr et al. 2019). With the potential withdrawal of glyphosate, finding alternative means of terminating cover crops is a key research requirement (Storr et al. 2019). Cover crops can be destroyed mechanically, including cultivations which mix the cover crop residues with the soil or by flailing, disking or rolling the shoot biomass, which result in a mulch on the soil surface (Hallama et al. 2018). Roll choppers which crush the shoots of cover crops rather than cutting or chopping them are another alternative to herbicide, requiring less energy than rotary mowers (Dorn et al. 2013). Cover crops can also be destroyed via grazing thereby providing an additional economic benefit to growers and an alternative winter forage crop. There has been limited research into different methods of cover crop destruction. Snapp & Borden (2005) evaluated the effect of destruction by mowing or spraying with glyphosate compared to direct incorporation of a rye/mustard/vetch cover crop in a greenhouse experiment. The authors suggested that management by mowing or glyphosate reduced the residue biomass by up to half and increased N mineralization by 10-100% compared to direct incorporation. Dorn et al. (2013) found that roll choppers were not as effective as glyphosate at reducing the weed pressure in the following cash crop, with yields lower following cover crops destroyed by roll-chopping compared to destruction using glyphosate. Nevin et al. (2020) studied decomposition of rye and vetch cover crops, destroyed chemically but with the following cash crop established either using reduced tillage (disc to 15cm depth) or by direct drilling. Using litter bags (either placed on the surface to mimic no till, or at 7.5cm depth) they saw that where the residues had been incorporated (rather than left on the surface) decomposition rates were higher. This was attributed to greater aeration, increased surface area (chopping effect of the tillage) and increased residue/soil contact. Cicek et al (2014) evaluated the effect of sheep grazing compared to using a blade roller to destroy two green manure crops (oat or oat/pea mix grown for a whole season rather than just over winter) in an organic mixed farming system in Canada, with the experiment repeated over three years. In all three studies, soil N availability (nitrate-N) was increased in the grazed compared to the mechanically destroyed treatments, and following wheat yields were either greater than or equal to those of the un-grazed plots.

Cover cropping tends to have greater positive effects on main crop performance in systems under reduced tillage/no-till than those under conventional tillage (i.e. where both cover and cash crops are established using reduced or no tillage; Hallama et al. 2018). Indeed, in the UK, cover crops tend to be used more frequently on reduced and no till systems compared to plough or power harrow-based systems (Storr et al. 2019). Further research is required to understand the potential benefits/disbenefits of different methods of cover crop destruction on establishment, yield and performance of the following cash crop as well their impact on subsequent crop available nutrient supply.

2.2.3. Economics of cover cropping - NFS case study (NIAB TAG, Norfolk)

The New Farming Systems (NFS) project was set up in 2007 and is on-going with support from the Morley Agricultural Foundation (TMAF) and the JC Mann Trust. The NFS experiment is located in Bullswood Field (Morley, Norfolk) on a medium sandy loam soil (Ashley series). Four cultivation techniques and two rotations are employed, resulting in 8 treatments; these treatments are outlined in Table 2.2. The experiment has a fully replicated factorial design with four replicates. Each plot is 12m x 36m to facilitate the use of farm scale equipment and techniques and all inputs are consistent with local best practice. Rotations alternate between winter cereals and combinable break crops, and rotations are differentiated further by the presence/absence of an autumn cover crop (radish, *Raphinus sativus*) before spring crops. Cover crops are typically sown in late August / early September and destroyed using glyphosate in the following January / February.

Table 2.2 Summary of NFS project rotation, cultivation and management treatments.

Rotation	2008 (Yr 1)	2009 (Yr 2)	2010 (Yr 3)	2011 (Yr 4)	2012 (Yr 5)	2013 (Yr 6)	2014 (Yr 7)	2015 (Yr 8)	2016 (Yr 9)	2017 (Yr 10)	2018 (Yr 11)
Without cover crop	ww	sosr	ww	sbn	ww	sbr	wosr	ww	so	ww	wbr
With cover crop	ww	sosr	ww	sbn	ww	sbr	wosr	ww	so	ww	wbr
Cover crop sown		✓		✓		✓			✓		

Key – ww (winter wheat), sosr (spring oilseed rape), wosr (winter oilseed rape), so (spring oats), sbn (spring bean), sbr (spring barley). Wbr (winter barley)

Cultivation	
Annual plough	Inversion tillage treatment is ploughed every year to c. 20-25 cm
Deep tillage	Treatment is cultivated to c. 20-25 cm using a non-inversion technique
Shallow tillage	Treatment is cultivated to c. 10 cm using a non-inversion technique

Cover crop: radish cover crop autumn sown and destroyed overwinter ahead of spring sown crops

Cultivation approaches follow an annual plough inversion tillage approach (*c*. 20-25cm), deep (*c*. 20-25cm) non-inversion tillage, shallow (*c*. 10cm) non-inversion tillage (typically using tine and disc based systems), or a managed system (decided on an annual basis, but not included in this report). Non-inversion treatments used a Sumo Trio cultivator.

Crop and yields are recorded each season with a Sampo plot combine. Oilseed rape crops grown in 2009 and 2014 were excluded from the analyses due to the known associated yield reductions from sowing brassica type species in short rotations (Stobart and Morris, 2015). Margin data are based on a gross output minus direct input and machinery costs for prices relevant to each production season. All crop prices and input costs are determined annually through market bulletin publications and in agreement with the project advisory committee. The cumulative margin of each system has been reported as the additive value in each year. Margins included the associated costs of the cover crop, where applicable (including the associated costs for seed and establishment), which were typically *c.* £40-£60/ha.

The cumulative margin showed little difference between cultivation methods (see Figure 2-2). Cumulative margins were highest under deep tillage (mean £5,297) and lowest under Plough Tillage (mean £5,160) with shallow tillage being intermediate (mean £5,216), reflecting differences in cultivation costs. There was little effect of cover crops either increasing, or decreasing margins over the 8 year period (with three iterations of cover crops sown). There was a slight tendency for the shallow tillage to show a slight (*c*. 2-4%) increase in margin with cover crop compared to no cover crop, although this was not significant. The impact of crop species grown had a greater impact on margin than either cultivation or cover crop, particularly following low spring bean (2011) and spring barley yields (2013).

There was no significant impact of cultivation method on crop yields (Table 2.3). The inclusion of a cover crop also had no significant impact on yield in all crops except the winter oilseed rape (2014) where yield was significantly decreased by the inclusion of a brassica cover crop (Stobart and Morris, 2015). When considering margins across the rotation at NFS the inclusion of cover crops (including the associated costs for seed and establishment c. £40-60/ha) resulted in no significant increase, or decrease in overall margin, irrespective of tillage approach. The cumulative margin, across cultivation, with the inclusion of cover crops was £5194 compared to £5254 without the inclusion of cover crops.

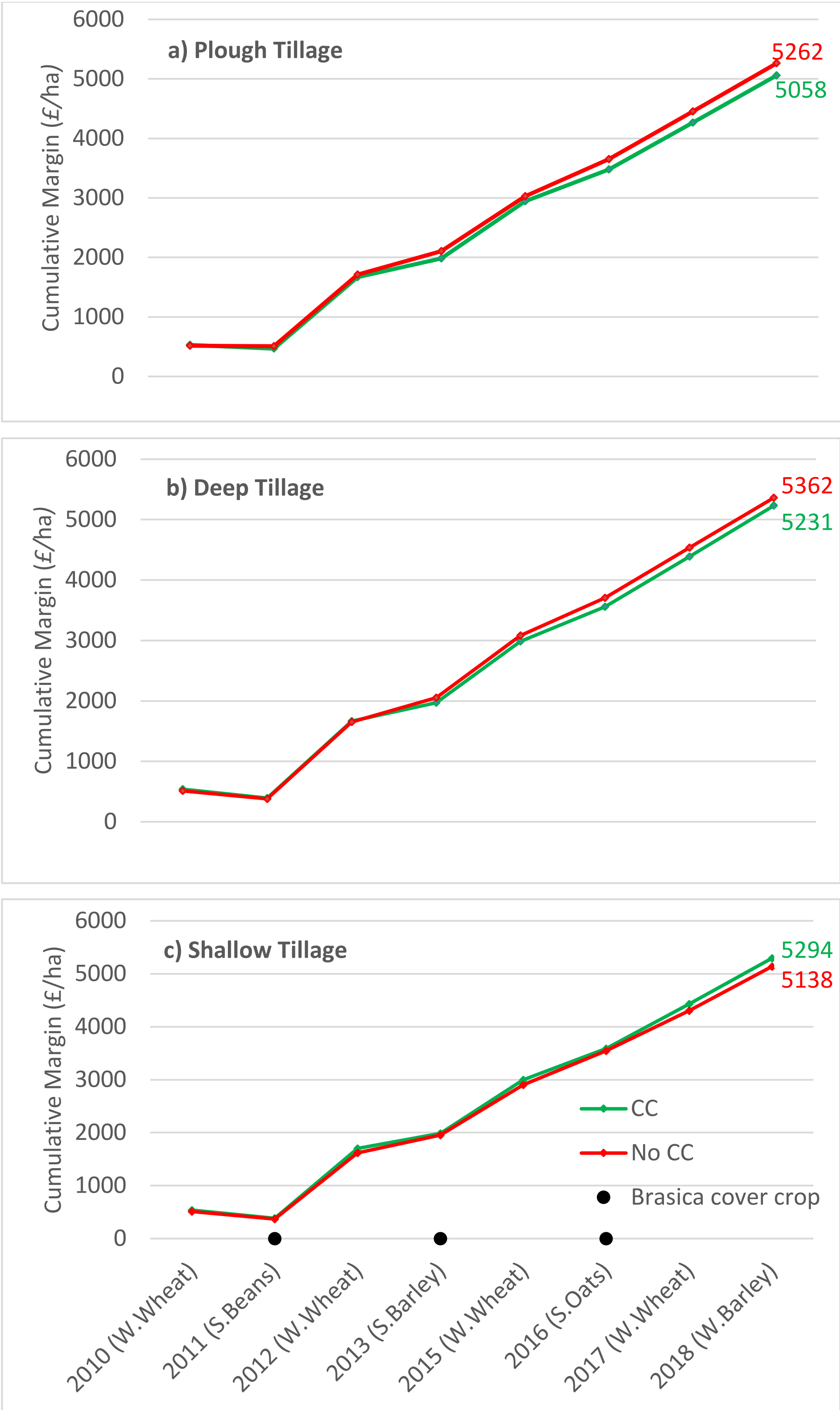


Figure 2-2 Cumulative margins (£/ha) ± cover crops under a) plough; b) deep tillage and c) shallow tillage from 2010 to 2018 excluding oilseed rape crops (2009 and 2014).

Table 2.3 Crop yields (t/ha) for the years 2008-2018.

		W.Wheat	S.OSR	W.Wheat	S.Beans	WW	S.Barley	W.0SR	W.Wheat	S.Oats	W.Wheat	W.Barley
Cultivation	**Cover crop (CC)**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Plough	CC	12.6	1.6	7.8	1.4	10.4	5.3	3.3	10.8	8.0	9.8	7.5
Plough	No CC	12.9	1.5	7.7	1.5	10.4	5.3	3.6	10.5	8.3	9.9	7.6
Deep	CC	12.4	1.3	7.5	0.9	10.5	5.1	3.7	11.1	8.1	9.9	7.6
Deep	No CC	12.5	1.6	7.3	0.8	10.5	5.2	4.0	11.2	8.1	9.9	7.5
Shallow	CC	12.4	1.5	7.4	0.8	10.7	4.9	4.0	10.9	8.2	9.9	7.8
Shallow	No CC	12.5	1.3	7.2	0.7	10.3	4.7	4.2	10.4	8.2	9.3	7.6
	P=0.05	*0.553*	*0.558*	*0.902*	*0.379*	*0.252*	*0.968*	*0.970*	*0.760*	*0.650*	*0.512*	*0.788*
	LSD	*0.58*	*0.47*	*0.87*	*0.24*	*0.29*	*0.96*	*0.57*	*0.81*	*0.81*	*0.84*	*0.40*
Mean	CC	12.5	1.5	7.5	1.1	10.5	5.1	3.8	10.9	8.1	9.8	7.6
Mean	No CC	12.5	1.4	7.3	1.0	10.4	5.1	4.1	10.6	8.1	9.6	7.6
	P=0.05	*0.704*	*0.744*	*0.280*	*0.932*	*0.237*	*0.705*	*0.046*	*0.224*	*0.925*	*0.414*	*0.611*
	LSD	*0.29*	*0.24*	*0.44*	*0.12*	*0.15*	*0.48*	*0.29*	*0.41*	*0.41*	*0.42*	*0.20*

The interaction of brassica cover crop and primary tillage method on the yield of other crops in the rotation can be gauged using the NFS data presented in (Figure 2-3). Positive yield responses from the use of a cover crop are represented as values above the zero line and negative responses as values below. It should be noted that the values are ranked in order of response and not by year. The results suggest an interaction between cover crop yield response and tillage practice; with brassica cover crop use in conjunction with shallow non-inversion tillage more likely to give a positive yield response in this study. Interestingly the only appreciable negative value in the shallow non-inversion tillage system was in 2014, where oilseed rape followed repeated use of a brassica cover crop (Stobart & Morris 2015). It is likely that the use of lower tillage intensity allows the benefits of the cover crops (i.e. rooting and improved soil structure) to be better utilised across the rotation. The effect of the cover crops is less likely to be apparent in a plough based system as the mechanical disturbance by inversion tillage restructures the soil through physical and not biological means.

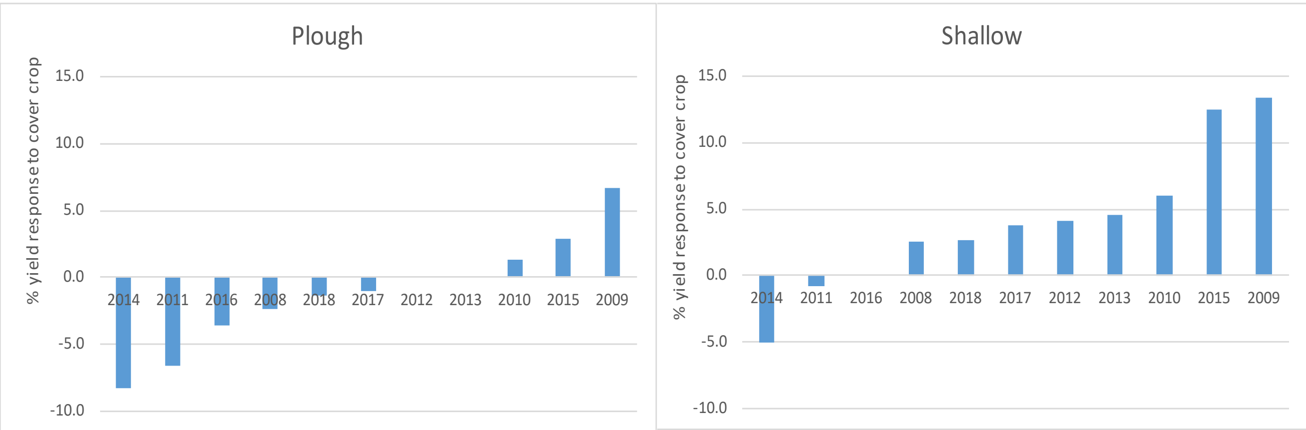


Figure 2-3 Yield response (%) to the rotational use of a brassica cover crop (grown before the spring sown break crops in the rotation) under a plough based or shallow non-inversion tillage system. Positive values are a benefit from rotational cover crop use. Crops in specific harvest years were: 2009 (spring oilseed rape), 2011 (spring beans), 2013 (spring barley), 2014 (winter oilseed rape), 2016 (spring oats), 2017 (winter barley) and 2010, 2012, 2015 and 2017 (winter wheat).

2.2.4. Literature review summary

It is evident from the literature that cover crops have a clear role in protecting soils over winter, retaining nutrients and therefore protecting water bodies. There is also evidence that cover crops, particularly when grown for a number of successive years in rotation, can result in improvements in soil physical, chemical and biological properties. Effects on subsequent crop yields are more variable and from an economic perspective the NFS project suggests small increases in gross margin are likely only after multiple years of cover cropping over a number of rotational cycles. There has been some research on how different cover crops root and the impact of the different rooting structure on crops and soils, but further work is required under UK conditions. Moreover, there is still considerable uncertainty regarding when nitrogen recovered by a cover crop is mineralised and made available for subsequent crops, and how cover crop destruction methods might affect this.

3. Cover Crop Replicated Large Plot Experiments

3.1. Methods

3.1.1. Experimental sites and treatments

Ten different cover crop treatments were compared with an uncovered control on large (24 x 6m) experimental plots established at three commercial farms: Stetchworth, Cambridgeshire (autumn 2016), Kneesall, Nottinghamshire (autumn 2017) and Wilberfoss, East Yorkshire (autumn 2017). The cropping history and underlying soil characteristics at each of the sites is given in Table 3.1.

Table 3.1 Characteristics and cropping at the large plot experimental sites

Site	1. Stetchworth, (Cambridgeshire)	2. Kneesall, (Nottinghamshire)	3. Wilberfoss (East Yorkshire)
Annual rainfall[1]	568 mm	650 mm	751 mm
Soil texture	Sandy loam	Clay loam	Sandy loam
Topsoil chemistry[2]:			
pH	7.7	7.1	6.3
Ext. P (mg/l)	13 Index 1	23 Index 2	17.2 Index 2
Ext. K (mg/l)	114 Index 1	215 Index 2+	121 Index 2-
Ext. Mg (mg/l)	55 Index 2	157 Index 3	49 Index 1
SOM (% LOI)	2.6	3.7	nd
Crop rotation[3]	WW, CC, SBa, Wba,	WW, CC, SBa, WOSR	WBa, CC, Sba, CC, SB

[1]30 year average rainfall from NIAB Cambridge, ADAS Gleadthorpe and ADAS High Mowthorpe weather stations (1980-2010); Note actual annual rainfall at the sites (averaged across the 2 years of experimentation – 2016-17 & 2017-18): 545mm at Stetchworth, 644mm at Kneesall & 404 mm at Wilberfoss) [2]Ext. P, K, Mg = Extractable phosphorus, potassium and magnesium; Index refers to the relative amounts of soil nutrients which are available to plants and range from 0 (deficient) to 9 (very large); SOM = Soil organic matter measured using loss on ignition (LOI); nd = not determined. [3]Crop rotation during the experimental period (2016-18 at site 1; 2017-19 at sites 2 & 3): CC = cover crop; SBa = Spring Barley, WBa = Winter barley, WW = winter wheat, WOSR = Winter oilseed rape, SB = sugar beet. nd: not determined

The cover crop treatments were selected to include species representative of the main cover crop categories and associated benefits: brassicas (nutrient uptake and soil structure), legumes (soil fertility), grasses and cereals (ground cover and nutrient uptake) and 'others' (e.g. Phacelia and Buckwheat – nutrient scavengers which don't cause rotational conflicts). A total of 7 individual species together with three combinations (of increasing complexity) of these species were evaluated in order to understand the performance and benefits of the species grown as 'straights' or 'mixes'; Table 3.2. There were three replicates of each treatment arranged in a randomised block design.

Table 3.2. Cover crop treatments at each site

Treatment number	Treatment: cover crop species (and variety)	Seed rate	Justification for inclusion
1.	No cover (bare/weedy stubble)	-	
Straights (individual species):			
2.	Oil Radish (Terranova)	10 kg/ha	Deep rooting and fast growing brassica
3.	Spring Oats (Canyon)	50 kg/ha	Cheap and fast growing cereal
4.	Rye (Inspector)	50 kg/ha	Data required for this fast growing cereal under UK conditions
5.	Vetch (Amelia)	60 kg/ha	Large-seeded legume
6.	Crimson Clover (Contea)	10 kg/ha	Small-seeded legume
7.	Buckwheat (Lileja)	70 kg/ha	P uptake; frost sensitive
8.	Phacelia (Natra)	10 kg/ha	Deep rooting, N uptake, semi-frost sensitive
Mixes:			
9.	Spring Oats (83%) & Crimson Clover (17%)	36 kg/ha	Relatively cheap basic benchmark mix
10.	Oilseed Radish (30%), Phacelia (20%) & Buckwheat (50%)	20 kg/ha	Compaction alleviation; different frost-sensitivities to provide varying cover
11.	Spring Oats (53%), Crimson Clover (11%), Oilseed Radish (11%), Phacelia (6%) & Buckwheat (19%)	37.5 kg/ha	To evaluate whether added biodiversity gives additional benefit

The cover crops were drilled in late September (21/9/16) at Stetchworth, and in mid-August at Kneesall (23/8/17) and Wilberfoss (22/8/17). Table 3.3 gives details of the operations undertaken to establish the treatments at each site; the cover crops were destroyed using glyphosate in mid-February at Stetchworth and mid-March at Kneesall and Wilberfoss, with spring barley (cv. Planet) subsequently established using minimum tillage at all sites. The following cash crops (spring and winter crops) were managed by the host farmer and grown according to best farm practice, using commercially recommended seed rates, with crop protection products applied according to good agricultural practice to control weeds, pests and diseases and manufactured fertiliser applied according to the farm agronomist's advice. At Stetchworth, the cover crop treatments were also repeated over winter 2018-19 ahead of sugar beet and funded by BBRO; the same plots and seed rates were used as those in 2016, with drilling undertaken on 30th August 2018. Only cover crop yield and N uptake were determined on this second cycle of cover cropping, with assessments of seed bed condition and final sugar beet yield determined by BBRO (not included in this report).

Table 3.3 Site husbandry

Site	1. Stetchworth, (Cambridgeshire)	2. Kneesall, (Nottinghamshire)	3. Wilberfoss (East Yorkshire)
Site preparation	Light cultivation post-harvest with volunteers subsequently removed using glyphosate	Light cultivation post-harvest	Light cultivation post-harvest with volunteers subsequently removed using glyphosate
Cover crop establishment:			
Method	Sulky drill with Suffolk coulters set on a power harrow set to move the trash only; followed by Cambridge roll		
Date	21/9/16	23/8/17	22/8/17
Slug control	Yes	Yes	No
Cover crop destruction:			
Method	Glyphosate	Glyphosate	Glyphosate
Date	20/2/17	20/2/18	5/3/18
Spring barley establishment:			
Method	Light harrow; Vaderstad drill and roll	Horsch focus drill	Vaderstad drill and roll
Date	13/3/17	24/4/18	16/4/18
Harvest date	15/8/17	9/8/18	7/8/18
Winter crop:	Winter barley	Winter oilseed rape	Mustard cover crop[1]
Method	Light disc and drill	Disc & tine cultivation and Horsch pronto drill	Light disc and drill
Date	1/10/17	31/8/18	17/9/18
Harvest date	10/7/18	1/8/19	4/2/19

[1]A change in the planned rotation at Wilberfoss: no winter cash crop; the grower planted a mustard cover crop ahead of sugar beet, so final assessments (yield and soil properties) were determined at destruction of the mustard.

3.1.2. Soil assessments

Mineral nitrogen (i.e. ammonium-N + nitrate-N) in the soil profile (0-90cm) was determined in 30cm depth increments (0-30, 30-60 and 60-90cm) prior to cover cropping on the control treatment, and then on all treatments at cover crop destruction, post-harvest of the spring cash crop and post-harvest of the winter cash crop (the latter was only performed at the Stetchworth experimental site).

The moisture content of the soil profile (0-90cm), penetration resistance (to 45cm depth, measured using a penetrologger recording every 2.5cm), and soil bulk density at 25-30cm (measured using 5cm diameter intact cores) was determined after cover crop destruction, but before the spring crop was drilled. Measurements were repeated in the spring of the winter crop (at Wilberfoss this was post-destruction of the mustard cover crop), together with an assessment of topsoil structural condition using the Visual Evaluation of Soil Structure (VESS) methodology (Guimaraes et al., 2011). Earthworm numbers present in a 40 x 20 x 25cm deep cube of soil (0.08m^2 surface area), were counted for 5 minutes using the hand-sorting method (Schmidt 2001). The earthworms collected were sorted into juveniles and adults, with the adult worms identified to functional group level; i.e. epigeic (litter-dwellers), endogeic (topsoil worms) and anecic (deep burrowing worms). A topsoil (0-15cm) sample was also taken at this time for the determination of soil organic matter (% loss on ignition and % organic carbon by dumas method) and total nitrogen content.

3.1.3. Cover crop growth and rooting

The success of cover crop establishment (speed and level of ground cover) was estimated using a hand-held CropScan meter on three occasions (3-4 weeks, 5-6 weeks and 7-8 weeks) post drilling. On each occasion, the Normalised Difference Vegetation Index (NDVI) was recorded, with a value of 1.0 indicating complete green cover (zero = bare soil).

Cover crop root length and root dry matter was determined 7-8 weeks post establishment by digging up 10 randomly located plants per plot (except for mix 2 where 12 plants were dug up to give equal proportions of each species in the sample). Where there was a mix of species equal numbers of each plant species were sampled (i.e. five plants each of mix 1, four plants each of mix 2, and two plants each of mix 3). Roots were separated from the shoot and washed using a DELTA-T root washer with 550 micron filters. The root samples were scanned using the winRHIZO root analysis package (Regent Instruments Ltd, Quebec City, Canada) and root measurements (total length, mean diameter and surface area) calculated. The root samples were dried in an oven at 80°C for 48 h (or until there was no further weight loss) and the sample dry weights were recorded.

Rooting to 60cm depth (in 20cm depth increments) was also determined within a week of cover crop destruction, by taking 6 cores per plot (3 cores from between the crop rows, 3 from between the plants within a row) and bulked together to give a single sample per depth per plot. This type of sampling excludes the storage tap root of the oil radish. Roots were separated from the soil using the root washer and scanned as described above. Root numbers were combined with the root lengths to calculate the specific root length. The specific root length (SRL) is a measure of the length of root per unit of root biomass, expressed as metres per gramme. Plants with a high SRL build more root length for a given amount of root biomass.

Cover crop above ground biomass (dry matter yield) and nitrogen (N) uptake were determined by cutting the above ground biomass to ground level from a 0.5 x 0.5m quadrat placed randomly on each plot. As buckwheat was known to be frost sensitive, cuts from this treatment were taken in November. For all other treatments, the biomass was determined just prior to destruction. Total P uptake was determined on selected treatments (numbers 1, 7, 9, 10 and 11; Table 3.2).

3.1.4. Cash crop growth and rooting

The success of spring barley establishment (speed and level of ground cover) was estimated using a hand-held CropScan meter on three occasions post-drilling. Rooting to depth was determined at anthesis (*c*. GS61-69) by taking 6 cores per plot with roots washed and scanned as described above (Section 3.1.3). Total above ground biomass and N uptake was determined pre-harvest by cutting the crop to ground level from a 0.5 x 0.5m quadrat placed randomly on each plot, with final grain yields measured at harvest using a plot combine and samples analysed for grain N offtake. Total above ground biomass, N uptake, grain/seed yield and N content was also determined on the winter cash crop in a similar manner.

3.1.5. Cost benefit analysis

Margin data were based on a gross output minus direct input and machinery costs for prices relevant to each production season. All crop prices and input costs were determined annually through market bulletin publications, with field machinery operations (Table 3.4) taken from the Central Association of Agricultural Valuers (CAAV) guide to the costings of agricultural operations (CAAV, 2017 and 2018). Typical cover crop seed rates and prices are shown in Table 3.5. A template to calculate margins is provided in Appendix A – Cost benefit template.

Cumulative margin data over two seasons, i.e. spring crop preceded by cover crop then followed with winter cropping, was expressed as mean margin responses for each harvest year in £/ha (based on spot prices in individual seasons). A breakdown of costs is provided in the cumulative margin tables (Tables 3-8, 3-9 and 3-10) and includes the following:

- Cover crop establishment and destruction costs– Includes seed, sprays and cultivations (where necessary)
- Cash crop costs – Includes field machinery operations including cultivations, fertiliser and spraying applications and harvesting
- Cash crop seed costs

Table 3.4: Typical machinery costs

Operation	**Typical operational cost (£/ha)**
Plough and press	58.60
Tine / disc cultivator	42.85
Disc	21.55 – 32.25
Press	23.00 – 27.10
Straw Harrow	19.95
Slug pelleting	2.50
Strip till drill	32.85
Direct drill (disc)	38.55
Direct drill (tine)	32.85
Cultivator drill	38.55 – 41.25
Roll	10.65 – 10.95
Fertiliser spreader	6.65 – 6.80
Sprayer	8.75 – 9.30
Combine	99.60
Plough and press	58.60
Tine / disc cultivator	42.85

Prices taken from CAAV publication 230 (2017) and 232 (2018).

Table 3.5 Typical cover crop seed rates and prices

Species	Seed rate (kg/ha)	Seed cost (£/kg)	Typical cost (£/ha)
Straights (individual species):			
Oil Radish	10	2.91	29.10
Spring Oats	50	0.55	27.50
Rye	50	0.71	35.50
Vetch	60	1.48	88.80
Crimson Clover	10	4.52	45.20
Buckwheat	70	1.84	128.80
Phacelia	10	5.03	50.30
Mixes:			
Spring oats (83%) and Crimson Clover (17%)	36	1.58	56.88
Oilseed Radish (30%), Phacelia (20%) and Buckwheat (50%)	20	3.37	67.40
Spring Oats (53%), Crimson Clover (11%), Oilseed Radish (11%), Phacelia (6%) and Buckwheat (19%)	37.5	2.15	80.63

Note: Prices indicative of an average of supplier prices. Due to a 'mixing cost' fee prices won't necessarily match directly between straights and mixes.

3.1.6. Statistical analysis

At each experimental site, the effect of the different cover crop treatments on soil properties and crop performance was evaluated using conventional analysis of variance (ANOVA) and comparison of P-values. A separate ANOVA was carried out at each site together with a cross site meta-analysis using REML to evaluate the overall effect of the different cover crop treatments by comparison of F-values (using Genstat version 16; VSN International Ltd, 2010).

3.2. Results

3.2.1. Cover crop performance

The establishment and subsequent growth of the cover crop treatments at Stetchworth (drilled 21st September 2016) was poor compared to Kneesall and Wilberfoss where cover crops were drilled a month earlier (22 and 23rd August 2017); Figure 3-1.

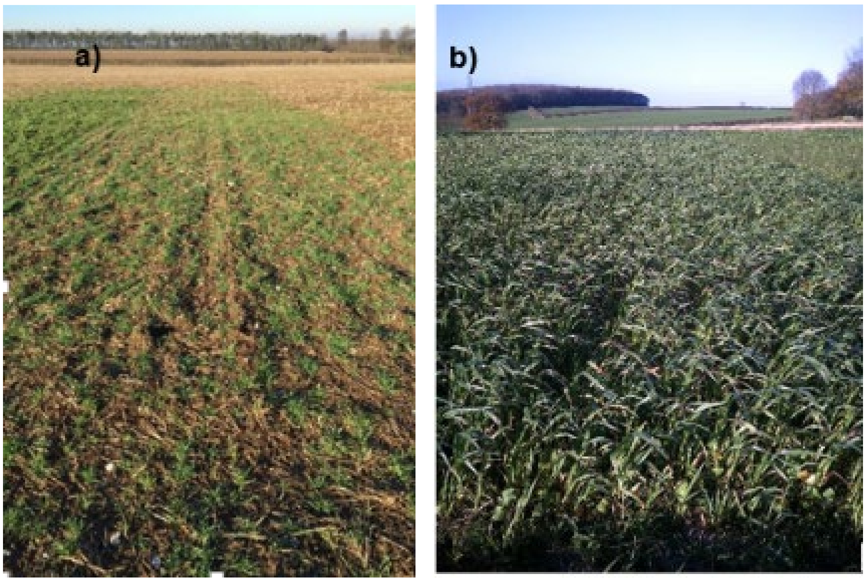


Figure 3-1 Effect of drilling date on cover crop performance: a) Oats at Stetchworth in January 2017 (drilled Sept. 2016) and b) Oats at Kneesall in November 2017 (drilled Aug. 2017).

Cover crop green biomass measurements (Figure 3-2, Figure 3-3, Figure 3-4) showed that at each of the sites the control and the clover cover crop (and the oats at Wilberfoss) had the lowest NDVI values. At Stetchworth, there were significant (P<0.001) differences between the treatments on each scan date. Generally, phacelia, radish, mix 2 and mix 3 (ie. the mixes that contained these two species) had the highest NDVI values.
At Kneesall, there were also significant differences between treatments on each assessment date (P<0.001 on the first two dates and P<0.01 on the last date). Generally (from the first two scan dates) mix 2, buckwheat, and radish had the highest NDVI readings.

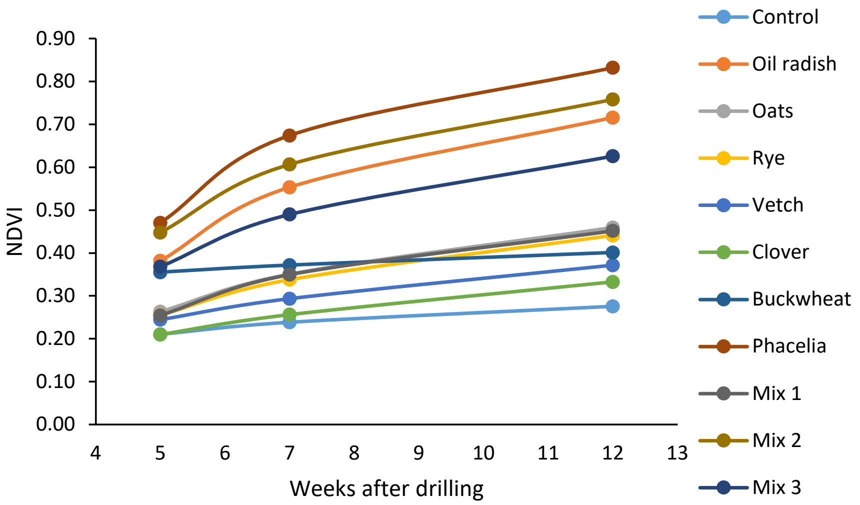


Figure 3-2 Stetchworth normalized difference vegetation index (NDVI) values measured on three dates after drilling cover crop drilling: 5 weeks, 28/10/2016; 7 weeks, 11/11/2016 and 12 weeks, 15/12/2016.

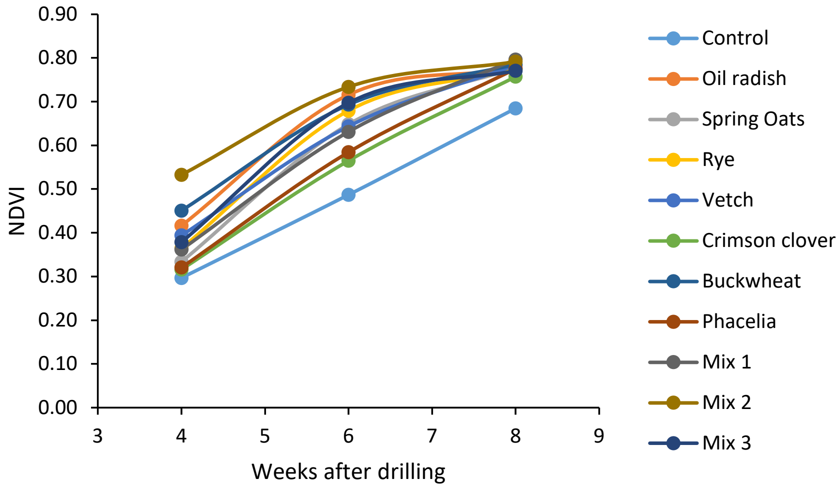


Figure 3-3 Kneesall normalized difference vegetation index (NDVI) values measured on three dates after drilling cover crop drilling:4 weeks, 20/09/2017; 6 weeks, 05/10/2026 and 8 weeks, 17/10/2016.

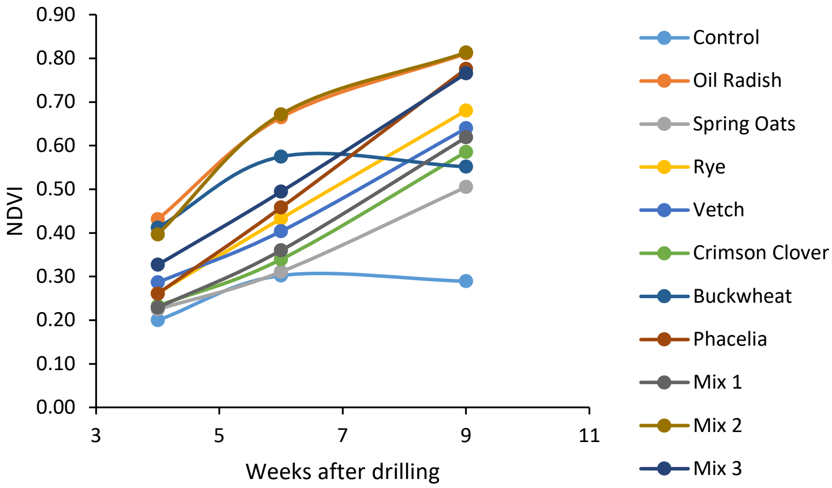


Figure 3-4 Wilberfoss normalized difference vegetation index (NDVI) values measured on three dates after drilling cover crop drilling:4 weeks, 22/09/2017; 6 weeks, 03/10/2017 and 9 weeks, 27/10/2017.

At Wilberfoss there were also statistically significant differences between the treatments on each scan date ($P<0.001$). Generally, the radish, buckwheat and mix 2 had high NDVI values. Over all the sites radish, buckwheat and mix 2 covers established quickly and produced a large amount of above ground green cover compared to the other cover crops.

As buckwheat is frost sensitive, this treatment was sampled in early November and produced 0.5, 0.8 and 2.0 t/ha above ground dry matter at Wilberfoss, Stetchworth and Kneesall, respectively. At Kneesall (which did not receive a pre-drilling glyphosate spray, Table 3.3), there was a large proportion of volunteers on this treatment. By the time of cover crop destruction (February), cover crop biomass at Stetchworth ranged from <0.1 t/ha (buckwheat – which had been destroyed by frost prior to this sampling so here biomass comprised largely of weeds and volunteers) to 1.1 t/ha (phacelia), compared to 0.5 t/ha (buckwheat/volunteers) to 3.5 t/ha (rye) at Wilberfoss, and 1.2 t/ha (radish) to 3.1 t/ha (mix 1) at Kneesall (Table 3.6). The control plots at Wilberfoss and particularly Kneesall also had a relatively high cover of volunteers (1.4 and 2.4 t/ha biomass at Wilberfoss and Kneesall, respectively). At Stetchworth, the second year of cover cropping (2018-2019) produced a higher biomass compared to the first year (2016-17), probably due to the earlier drilling date.

Across all the sites (excluding the repeat cover crop year at Stetchworth), cover crop biomass ranged from *c*. 0.8 - 2 t/ha, with rye producing the greatest amount of biomass and buckwheat the least ($P<0.05$), with a weedy stubble comprising largely of cereal volunteers also yielding on average 1 t/ha above ground dry matter (Figure 3-5).

Table 3.6 Cover crop performance (biomass and N uptake)

Site	Drilling date	Biomass (t/ha)	N uptake (kg/ha)	'Top performers'
Stetchworth	21/9/16	< 0.1 - 1.1; $P<0.001$	0.5 – 25; $P<0.001$	Phacelia and Oil Radish (and mixes including these species)
	20/8/18	0.2 – 2.2; P<0.001	6 – 65; P<0.001	
Kneesall	23/8/17	1.6 – 3.1; *NS*	35 – 88; $P<0.001$	Clover, Vetch and Mix 1
Wilberfoss	22/8/17	0.5 – 3.6; $P<0.05$	6 – 70; $P<0.001$	Mix 3 (N uptake); Rye (biomass)

NS = not statistically significant ($P>0.05$)

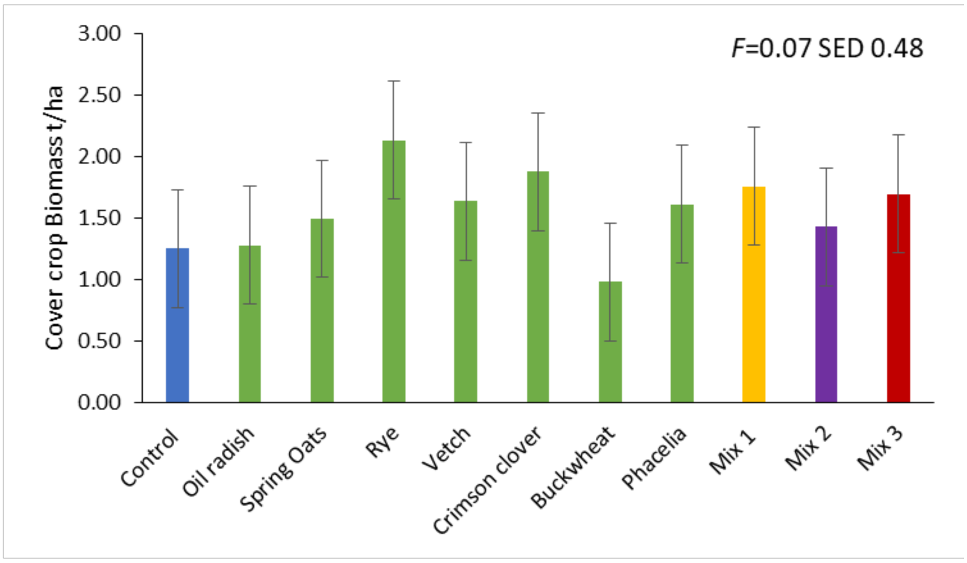


Figure 3-5 Cover crop above ground biomass prior to destruction (cross site averages); note the control treatment biomass comprised weeds/volunteers; buckwheat biomass was determined at an earlier sample timing to the other treatments, before it was destroyed by frost.

The nitrogen (N) content of the above ground biomass was greater where cover crop biomass was high (up to 70 kg/ha N uptake at Wilberfoss and 90 kg/ha at Kneesall compared to 25 kg/ha at Stetchworth in 2017 and 65 kg/ha in 2019; Table 3.6), although the greatest N uptake was not necessarily associated with the greatest above ground biomass. Vetch and clover 'recovered' the most N at Kneesall, with oil radish and phacelia (and mixes of these species) performing well at the other two sites ($P<0.05$; Table 3.6). Cross site analysis (excluding the second year of covers at Stetchworth) indicated that vetch, clover, oil radish and phacelia (and mixes of them) recovered an average of 35-50 kg/ha N compared to < 25 kg/ha N uptake on the control treatment (Figure 3-6; $P<0.001$).

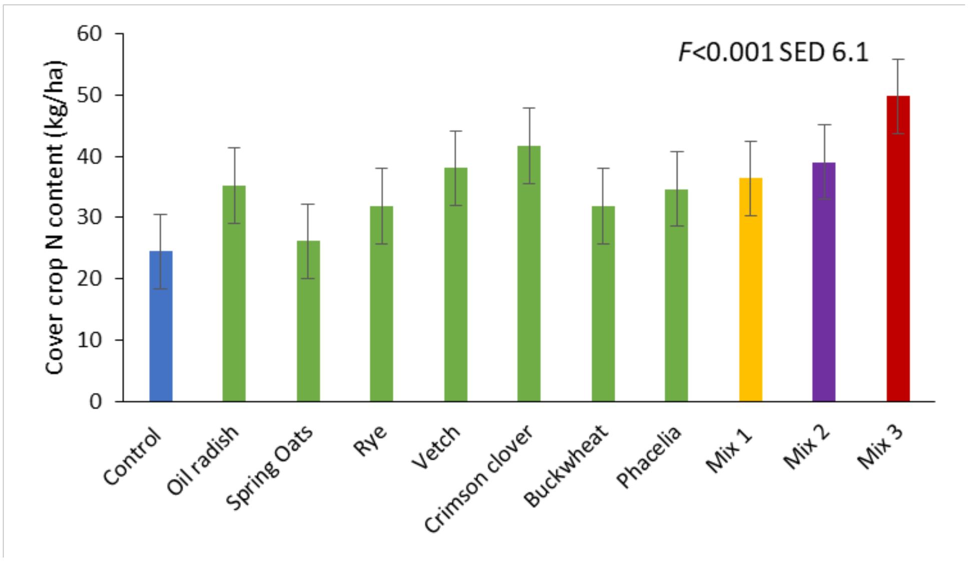


Figure 3-6 Cover crop N uptake (cross site averages); note the control treatment biomass comprised weeds/volunteers; buckwheat N content was determined at an earlier sample timing to the other treatments, before it was destroyed by frost.

Phosphorus (P) uptake was measured on selected treatments (funded by RAGT seeds), focusing on those which included buckwheat, to evaluate whether this species does 'scavenge' soil P. Higher P concentrations were measured in the above ground biomass where buckwheat had been grown (i.e as a straight, mix 2 and mix 3) compared to the control (volunteer/weeds) and mix 1 (oats and crimson clover); Figure 3-7 (*P*<0.001 for %P content, but not P uptake due to variability in dry matter production). However, due to the low biomass produced prior to frost destruction, the total amount of P taken up was very low where buckwheat was grown as a straight monoculture (*c.* 10 kg/ha P; Figure 3-7). Where it was part of a mix (50% of mix 2; 19% of mix 3) P concentrations of the above ground biomass were high, as was total P uptake, but these treatments were sampled after the buckwheat had been destroyed (whereas the monoculture buckwheat was sampled at an earlier date). The P content of the monoculture radish and phacelia treatments was not determined, so it was not possible to determine whether P uptake by these species had been enhanced by having buckwheat present in the mix. Note these results are from the Kneesall and Wilberfoss sites only (due to the low biomass production at Stetchworth).

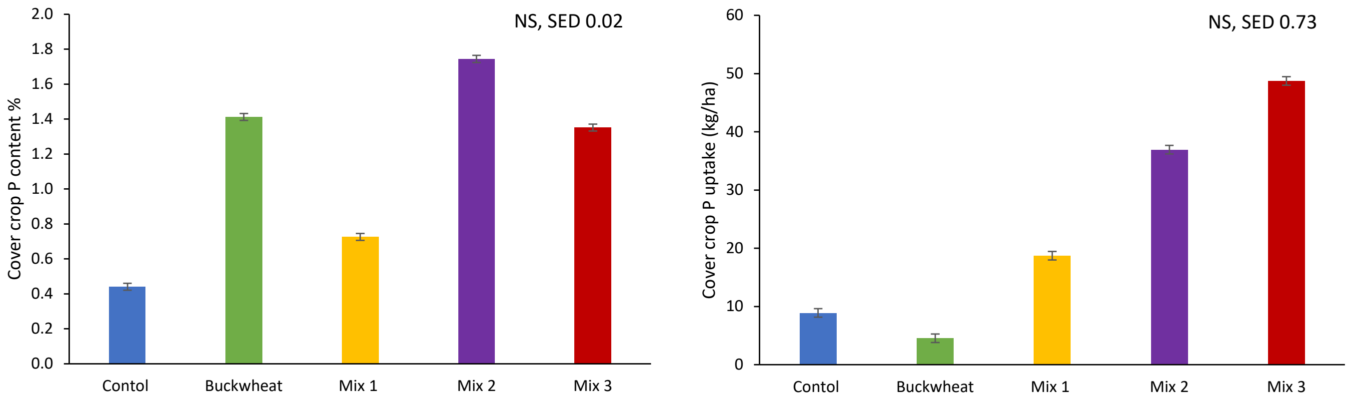


Figure 3-7 Cover crop P content (%) and P uptake (kg ha^{-1}) at cover crop destruction. 2017 sites only. Cross site averages. Note the control treatment comprised weeds/volunteers; buckwheat P content was determined at an earlier sample timing to the other treatments, before it was destroyed by frost.

Cover crop rooting

Tables of the key root traits of all the cover crop species and mixes evaluated at the three experimental sites, both early in the season (after *c.* 2 months growth) and at destruction can be found in Appendix B.

Early Rooting

Across all three sites, rye and radish had significantly (*F*<0.001) greater total root length per plant after *c.* 2 months growth at 395 cm and 258 cm respectively (Figure 3-8) compared to the other cover crop treatments and the control. Buckwheat had significantly (*F*<0.001) lower total root length at 99 cm compared to the other treatments and the control. Phacelia had the next lowest total root length at 118 cm. Radish also had the greatest root biomass (*F*<0.001) compared to the other treatments at 0.35 g per plant (Figure 3-9). Mix 2, which contained radish, had the next highest root biomass at 0.097 g per plant, which was significantly greater than the other cover crop treatments. Mix 3, which also contained radish had a root biomass of 0.079 g per plant which was significantly greater than the control and other straight cover crop treatments. Mix 1 had the lowest root biomass at 0.025 g per plant, and the control and buckwheat both had 0.29 g per plant root biomass.

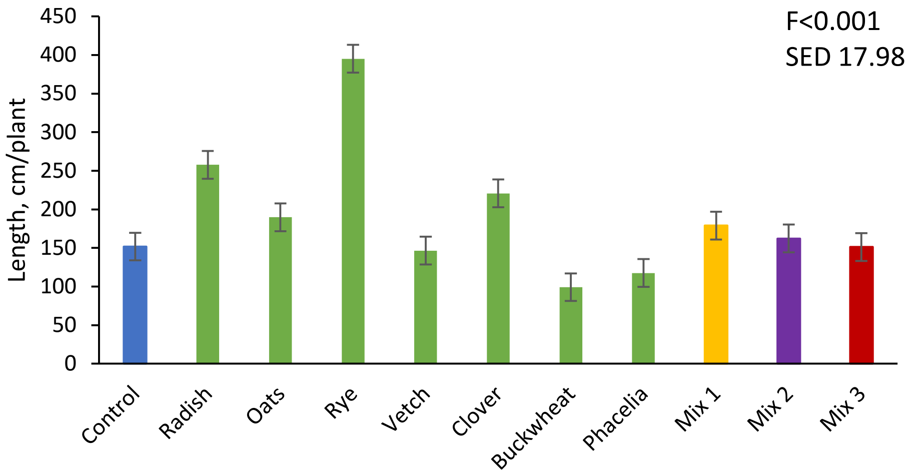


Figure 3-8 Cover crop root length, cm after c. two months growth. Cross site averages. Results are an average of 10 plants per plot (12 for mix 2), and exclude roots > 3mm in diameter which could not be scanned, with results expressed on a per plant basis. 5 plants/species, 4 plants/species and 2 plants/species were sampled from mix 1, 2 and 3, respectively. Sampling was undertaken prior to destruction of the buckwheat by frost.

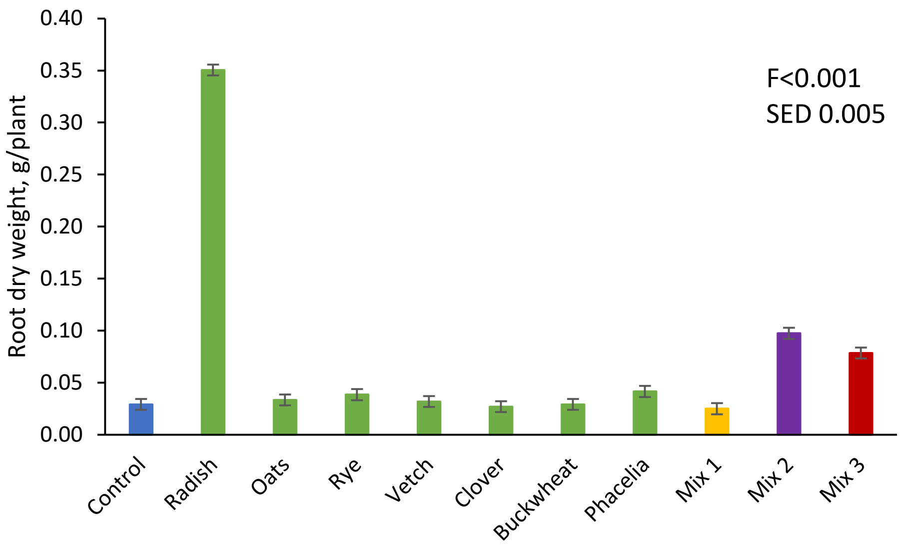


Figure 3-9 Cover crop root biomass, dry weight grams per plant, after c. two months growth. Cross site averages. Results are an average of 10 plants per plot (12 for mix 2) and include the radish taproot, with results expressed on a per plant basis. 5 plants/species, 4 plants/species and 2 plants/species were sampled from mix 1, 2 and 3, respectively. Sampling was undertaken prior to destruction of the buckwheat by frost.

At *c*. 2 months growth, vetch had the widest roots on average (*F*<0.001) compared to the control and other treatments (Figure 3-10) and rye had the narrowest roots (*F*<0.001) on average (note the results exclude any roots that were > 3mm diameter as these were unsuitable for root scanning and use of the WinRhizo software). Figure 3-11, shows the length of root in different diameter classes, there were statistically significant differences between the species in each diameter class. Clover, buckwheat, mix 2 and radish had over 90% of their root length in the 0-0.5 mm diameter class at *c*. 2 months growth. Whereas vetch and oats had less than 78% of their root length in this narrow diameter class. Vetch had the most root length in both the 0.5 – 1 mm and 1 – 1.5 mm classes compared to the other treatments with 21% and 3.7% of the root length respectively. The radish straight and mix 2 had less than 5% of the root length in the 0.5 -1 mm diameter class. Rye and clover had less than 1% of their root length in the 1-1.5 mm class. Vetch had the greatest percentage of root (4.3%) in the widest diameter class, >1.5 mm, and radish had the next greatest percentage at 3.8% length of root. Rye had the least amount of root in this class at 0.5%.

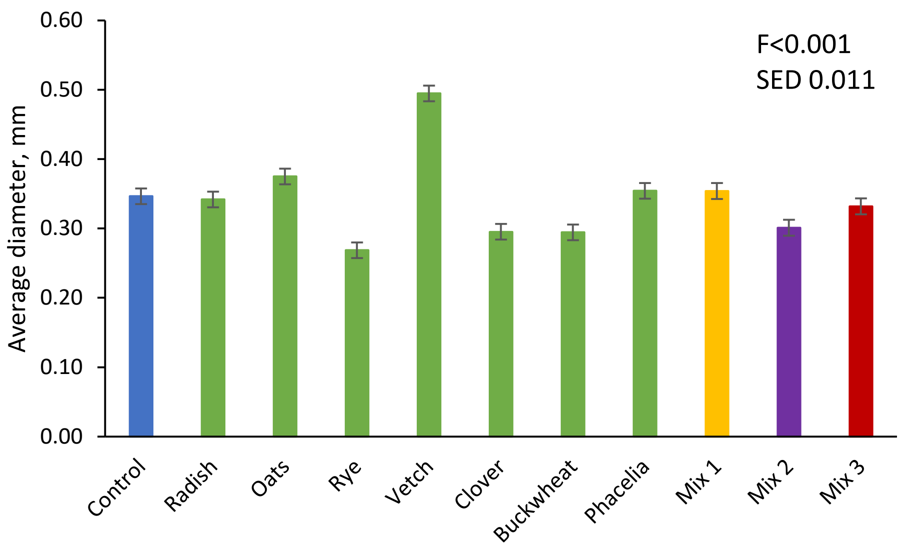


Figure 3-10 Cover crop root diameter, mm, after c. 2 months growth. Cross site averages. Results are an average of 10 plants per plot (12 for mix 2) and exclude roots > 3mm in diameter which could not be scanned, with results expressed on a per plant basis. 5 plants/species, 4 plants/species and 2 plants/species were sampled from mix 1, 2 and 3, respectively. Sampling was undertaken prior to destruction of the buckwheat by frost.

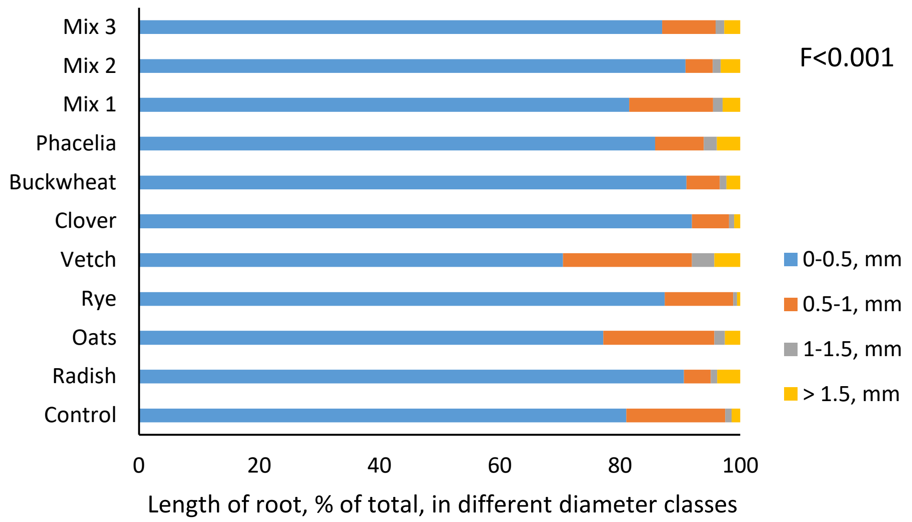


Figure 3-11 Length of cover crop roots in different diameter classes, as a percentage of the total root length. Cross site averages. Diameter classes: 0-0.5 mm, 0.5-1 mm, 1-1.5 mm, >1.5 mm. SED values for each diameter class: 0-0.5 mm, 1.33; 0.5-1 mm, 1.12; 1-1.5 mm, 0.18 and >1.5mm, 0.43. Results are an average of 10 plants per plot (12 for mix 2) and exclude roots > 3mm in diameter which could not be scanned. 5 plants/species, 4 plants/species and 2 plants/species were sampled from mix 1, 2 and 3, respectively. Sampling was undertaken prior to destruction of the buckwheat by frost.

Deep rooting at cover crop destruction

At cover crop destruction, phacelia and rye had the greatest average RLDs over all soil depths (Figure 3-12) at 3.5 cm/cm^3 and 3.4 cm/cm^3 while buckwheat and the control resulted in the lowest average RLDs of 1.2 cm/cm^3 (note roots on the buckwheat treatment would largely comprise weeds/volunteers as the buckwheat had been destroyed by frost). There was a significant interaction between the cover crop treatments and rooting depth. In the 0-20 cm soil horizon, phacelia and rye had the greatest RLDs of 8.7 and 8.1 cm/cm^3 and the control and buckwheat had the lowest RLDs at 2.5 cm/cm^3. In the 20-40 cm horizon there were no significant differences between the treatments, with values ranging between 0.5 and 1.5 cm/cm^3. In the 40 - 60 cm soil horizon, there were also no significant differences between the treatments with RLDs ranging between 0.4 and 0.7 cm/cm^3.

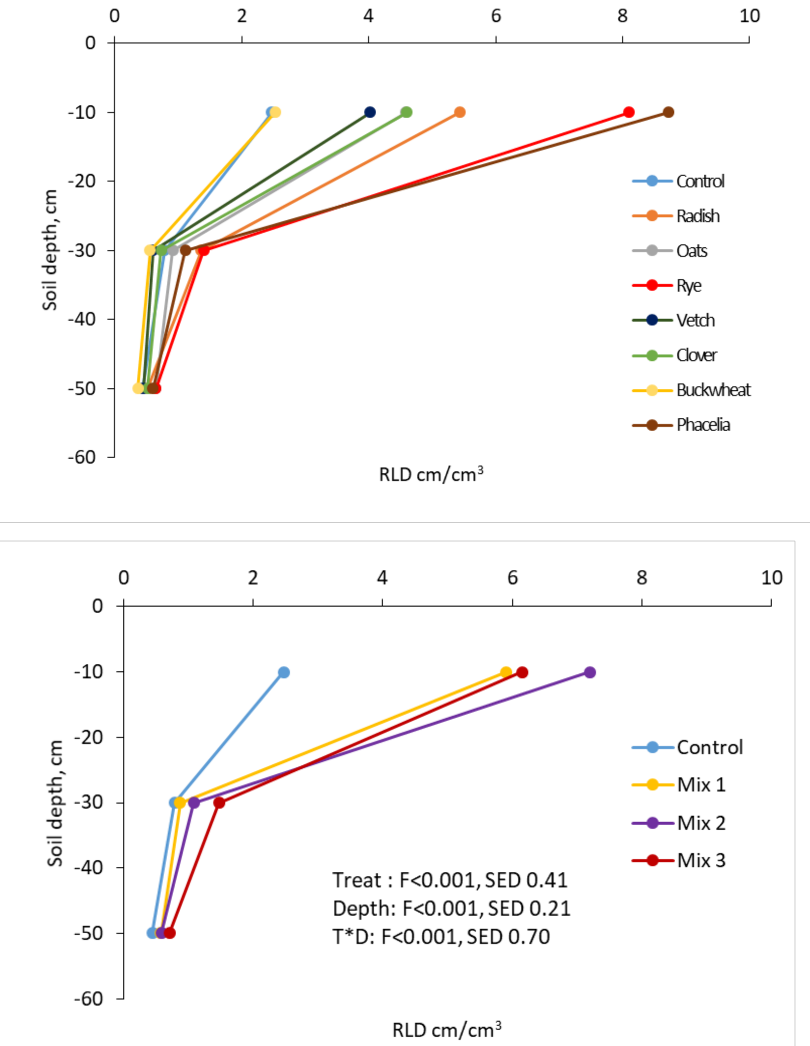
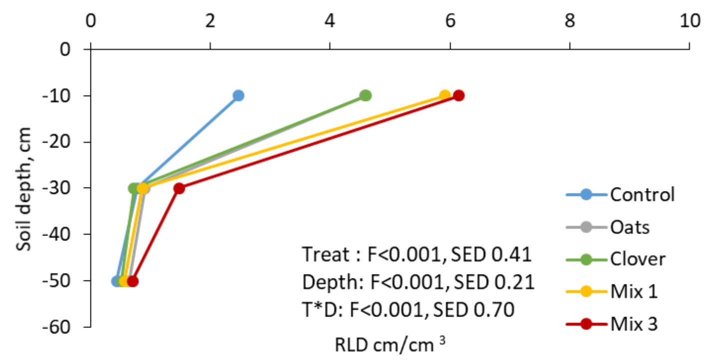


Figure 3-12 Cover crop root length density (RLD, cm/cm³) of the straights and mixes at cover crop destruction. Cross site averages. N.B. this doesn't include the radish taproot due to the nature of sampling. Note roots on the buckwheat treatment would largely comprise weeds/volunteers as the buckwheat had been destroyed by frost

The rye cover crop had a high root length both early in the season (*c.* 400 cm root/plant compared to 100-250 cm root/plant on the other cover crop treatments) and at destruction (average RLD of 3.4 cm/cm^3 to 60cm depth and 8.1 cm/cm^3 in the topsoil compared to 1.2-2.8 cm/cm^3 to 60cm on the other treatments, excluding phacelia). By comparison, although phacelia hadn't produced a lot of root length after two months growth (*c.* 120 cm root/plant), it had a high RLD at cover crop destruction (average of 3.5 cm/cm^3 to 60cm depth), especially in the topsoil (8.7 cm/cm^3). Buckwheat did not produce much root - only *c.* 100 cm/plant early in the season (prior to destruction by frost), with measurements taken later in the season associated with weed and volunteer growth on this treatment, which was virtually identical to the control treatment at an average of 1.2 cm/cm^3 to 60cm depth. Mix 1 produced a higher RLD than either of the individual component species in the mix (5.9 cm/cm^3 compared to 4.6 cm/cm^3 for both the oats and clover at 0-20cm depth P<0.05; Figure 3-13), which may suggest a stimulation of rooting by the individual species due to competition by being placed in a mix, termed 'over-yielding' in the literature (Kroon et al. 2012). However, based on the seed rates used (36 kg/ha mix 1, compared to 50 kg/ha for the oats and 10 kg/ha for the clover; Table 3.2) and proportion of seeds in the mix (83% oats) a RLD of 5.5 cm/cm³ would be expected if the plants in the mix rooted similarly to those as a straight, which is very similar to the actual RLD achieved (i.e. 5.9 cm/cm³).



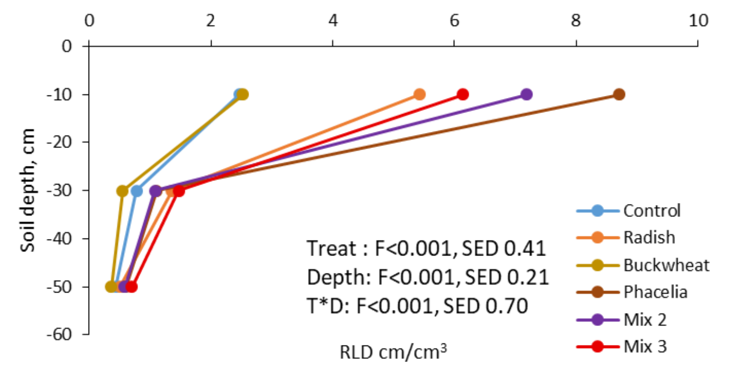


Figure 3-13 Cover crop root length density (RLD, cm/cm³) grouped by mix and component species at cover crop destruction. Cross site averages. N.B. this doesn't include the radish taproot due to the nature of sampling. Note roots on the buckwheat treatment would largely comprise weeds/volunteers as the buckwheat had been destroyed by frost

Rye, phacelia and mix 2 had the greatest root biomass averaged over all three soil horizons of 0.148, 0.139 and 0.123 mg/cm³ respectively (Figure 3-14). There were significant differences between the treatments (F<0.001) and a significant interaction with depth (F<0.001). In the top 0-20 cm of soil, phacelia and rye had significantly (F<0.001) greater root biomass than the other treatments. The control and buckwheat treatment had the lowest root biomass which was consistent with the RLD results. In the 20-40 cm horizon, rye, mix 3 and radish had the greatest root biomass of 0.087, 0.084 and 0.076 mg/cm³, while the buckwheat treatment (volunteers/weeds) and clover had the lowest at 0.036 and 0.048 mg cm^{-3} respectively. In the 40 - 60 cm horizon there were no significant differences between the treatments but they ranged from oats with 0.051 mg/cm³ to buckwheat treatment with 0.031 mg/cm³.

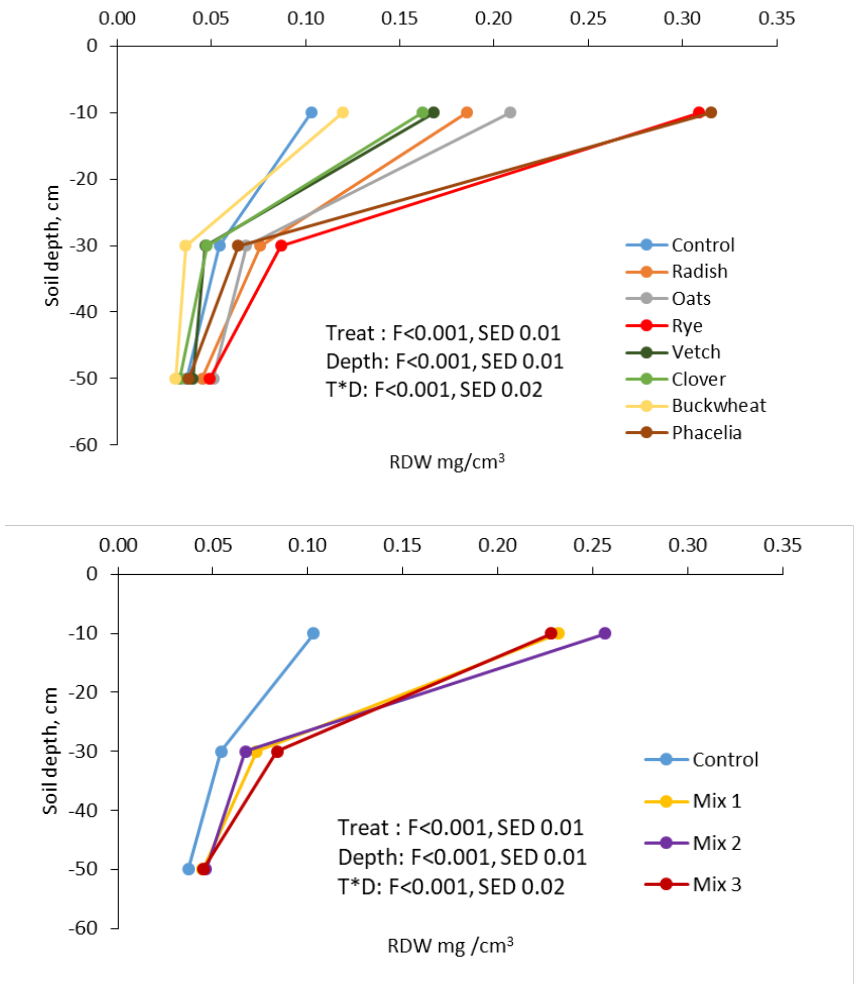


Figure 3-14 Cover crop root biomass (root dry weight RDW, mg/cm³) of the straights and mixes at cover crop destruction. Cross site averages. N.B. this doesn't include the radish taproot due to the nature of sampling. Note roots on the buckwheat treatment would largely comprise weeds/volunteers as the buckwheat had been destroyed by frost

Rye had the widest root diameter with a mean of 0.23 mm (Figure 3-15) which was significantly (F<0.001) greater than all of the other treatments, except mix 1. The control, phacelia, buckwheat and mix 2 treatments had the narrowest roots, at 0.19 mm. There was no significant interaction between cover crop treatments and depth.

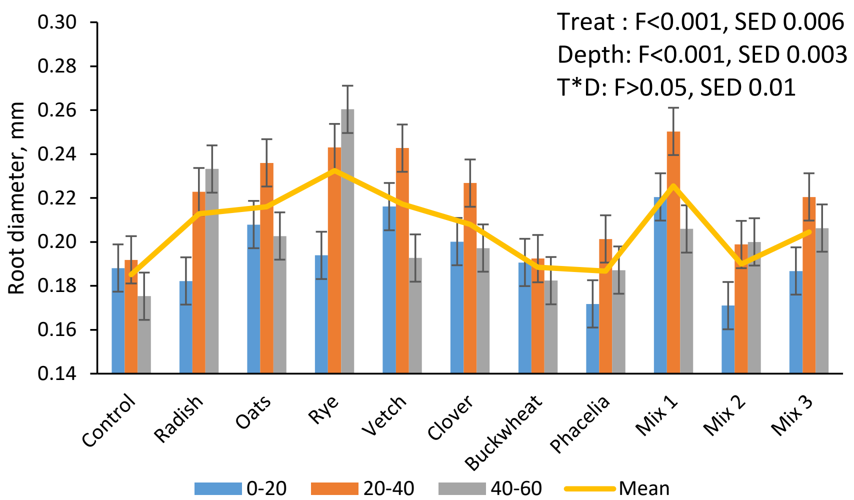


Figure 3-15 Cover crop root diameter, mm, at cover crop destruction. Cross site averages. N.B. this doesn't include the radish taproot due to the nature of sampling. Note roots on the buckwheat treatment would largely comprise weeds/volunteers as the buckwheat had been destroyed by frost

The specific root length (SRL, Figure 3-16) is a measure of the length of root in metres per unit of biomass in grammes. Plants with a high SRL build more root length for a given amount of biomass. SRL significantly decreased with increasing soil depth (*F*<0.001). Phacelia had the highest SRL on average at 268 m/g, while radish, mix 3 and mix 2 had the next highest SRLs at 255, 254 and 252 m/g respectively. Vetch had the lowest SRL at 188 m/g. These results suggest that phacelia may have explored more of the soil for a given root biomass compared to the vetch.

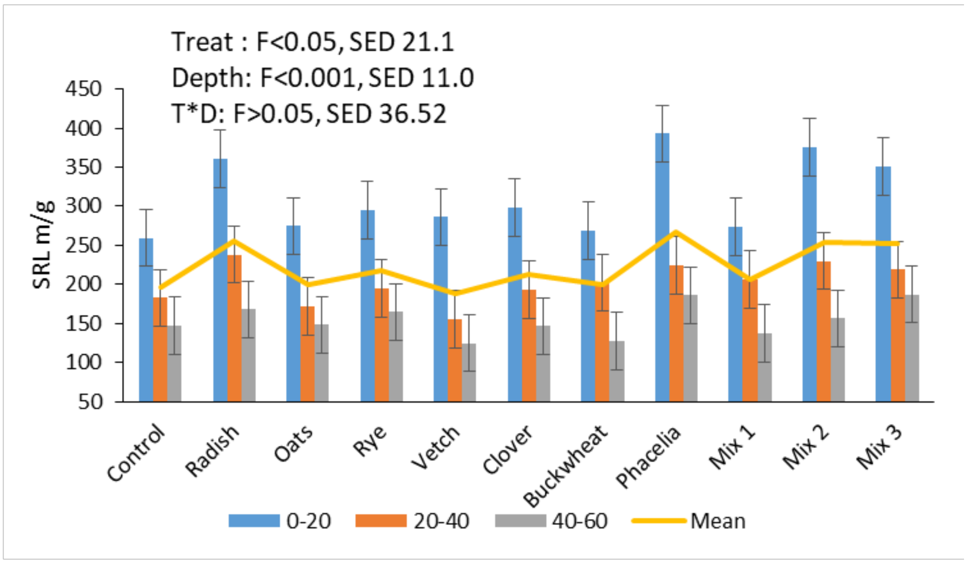


Figure 3-16 Cover crop specific root length, m/g at cover crop destruction. Cross site averages. N.B. this doesn't include the radish taproot due to the nature of sampling. Note roots on the buckwheat treatment would largely comprise weeds/volunteers as the buckwheat had been destroyed by frost

3.2.2. Effect of cover crop treatments on soil nitrogen supply

Soil mineral N (SMN - to 90 cm depth) was measured in the autumn prior to cover crop establishment and at destruction at both the Stetchworth and Kneesall sites. At Stetchworth, SMN at cover crop destruction varied with cover crop treatment ($P<0.05$) with the lowest SMN (25-30 kg/ha) measured where cover crop N uptake was greatest (i.e. phacelia, radish and mixes of these species) and the highest where there was minimal ground cover on the control treatment (at *c.*50 kg/ha). At Stetchworth, spring SMN levels were similar to those present in the autumn, which reflected low leaching losses during the drier than average winter (200mm rain fell over winter (Sept-Feb), which was *c.*70% of the 30 year average winter rainfall). Spring soil N supply ('SNS' = cover crop N + SMN) was very similar across the treatments ($P >0.05$), with virtually all of the SMN measured in the autumn recovered in the cover crop and soil in the spring (Figure 3-17).

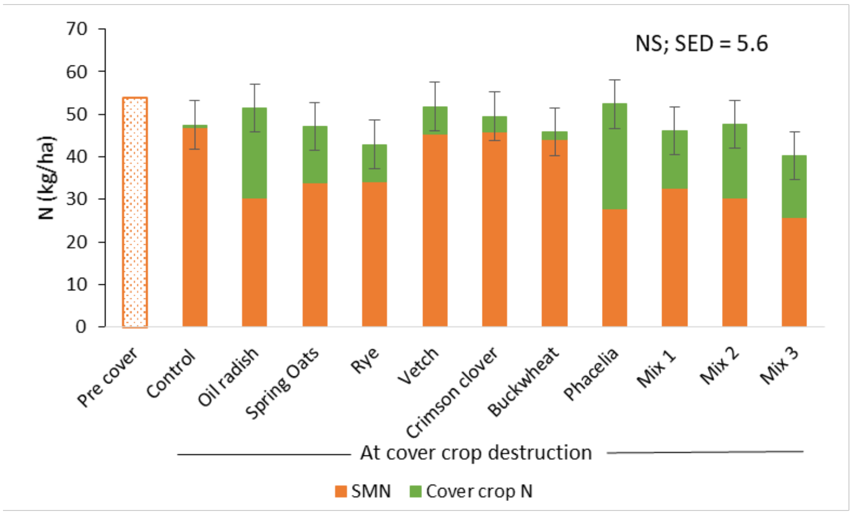


Figure 3-17 Change in soil mineral N over winter 2016-17 at Stetchworth and spring soil N supply (SNS = SMN + cover crop N)

At Kneesall, there was no treatment ($P>0.05$) effect on SMN measured at cover crop destruction, which had reduced across all treatments by *c.* 25 kg/ha over the winter period (Figure 3-18). However, the SMN present in the autumn (45 kg/ha N) was recovered by the above ground biomass (i.e. the cover crops or weeds and volunteers on the control treatment) on all treatments. Additional N (up to 60 kg/ha) that had been made available over the winter period, either from mineralisation of the soil organic matter/previous crop residues, nitrogen fixation or atmospheric deposition (Figure 3-18) was also recovered by the cover crop treatments. The highest spring SNS (105-110 kg/ha) was measured on the vetch and clover treatments ($P<0.001$) suggesting that N fixation had occurred over the winter period (an additional 20-25 kg/ha N compared to the control treatment, which had a good cover of volunteers but no legume species, and an SNS of 85 kg/ha). Rainfall over the winter period was similar to the 30 year average (at *c.*320 mm) and air temperatures ranged from 26° in late August to -6.5° in February (first frosts experienced in early December).

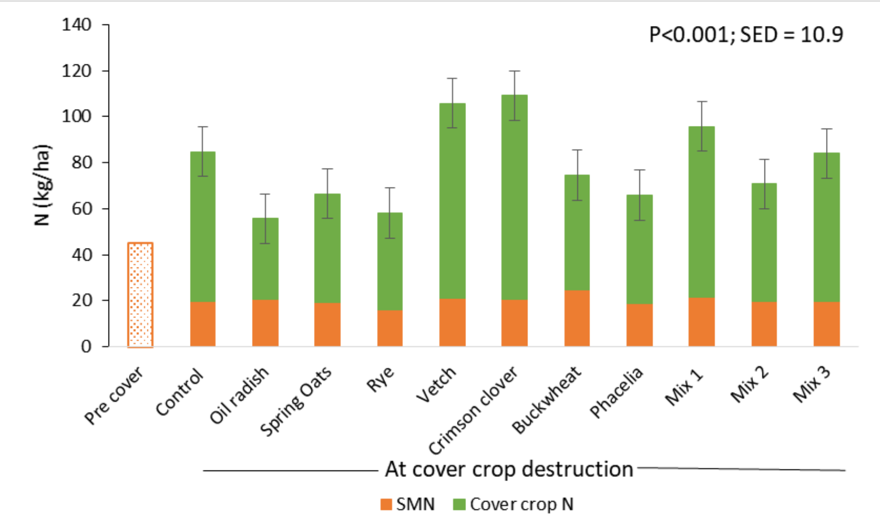


Figure 3-18 Change in soil mineral N over winter 2017-18 at Kneesall and spring soil N supply (SNS = SMN + cover crop N)

3.2.3. Effect of cover crop treatments on soil properties

The effect of the different cover crop treatments on soil properties was determined at cover crop destruction to evaluate the effect on seedbed properties (ahead of spring cropping), and a year after cover cropping (in the spring of the winter crop) to evaluate the potential longer-term benefits.

There was no significant effect of the different cover crop treatments on soil penetration resistance (to 45cm) or bulk density (at 25-30cm) at cover crop destruction ($P>0.05$). Figure 3-19 shows the typical penetration resistance profiles at each of the sites, with maximum resistances to 30cm of 1.1 MPa at the medium textured site (Kneesall), compared to 1.7 MPa (at 30cm) at the lighter textured sites (Stetchworth and Wilberfoss). Bulk density (at 25-30cm) was on average 1.26, 1.36 and 1.37 g/cm^3 at Stetchworth, Kneesall and Wilberfoss respectively, which reflected differences in soil type between sites.

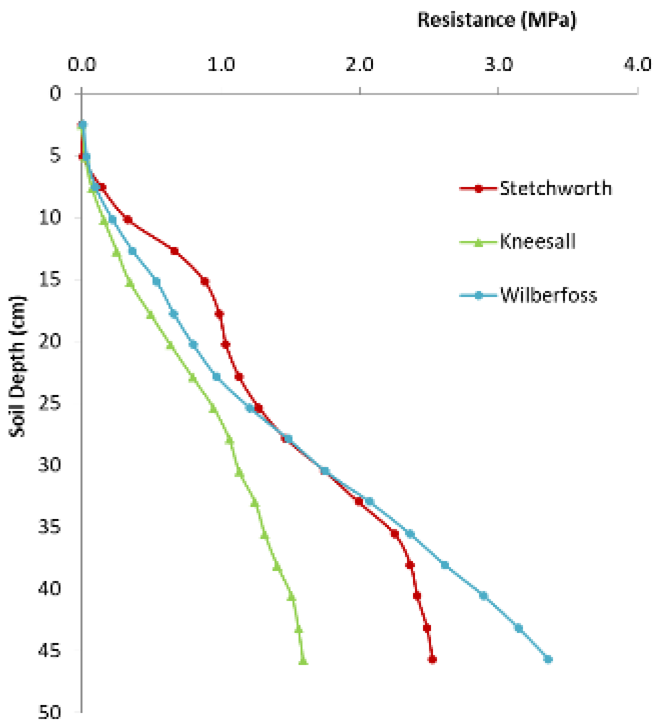


Figure 3-19 Average penetration resistance profiles at each of the sites (note there were no significant differences between treatments)

There was also no difference in soil moisture contents (to 90cm) at the lighter textured sites (Stetchworth and Wilberfoss; *P*>0.05). However, on the heavier textured soil at Kneesall, topsoil (0-30cm) moisture contents were higher on the cover crop treatments, particularly vetch, buckwheat (note although this was destroyed by frost in November, there were volunteers on this treatment which remained until destruction), phacelia and mix 2 (*P*<0.1; Figure 3-20); this did not extend to the deeper soil horizons (30-60 and 60-90cm) and was not related to above ground biomass.

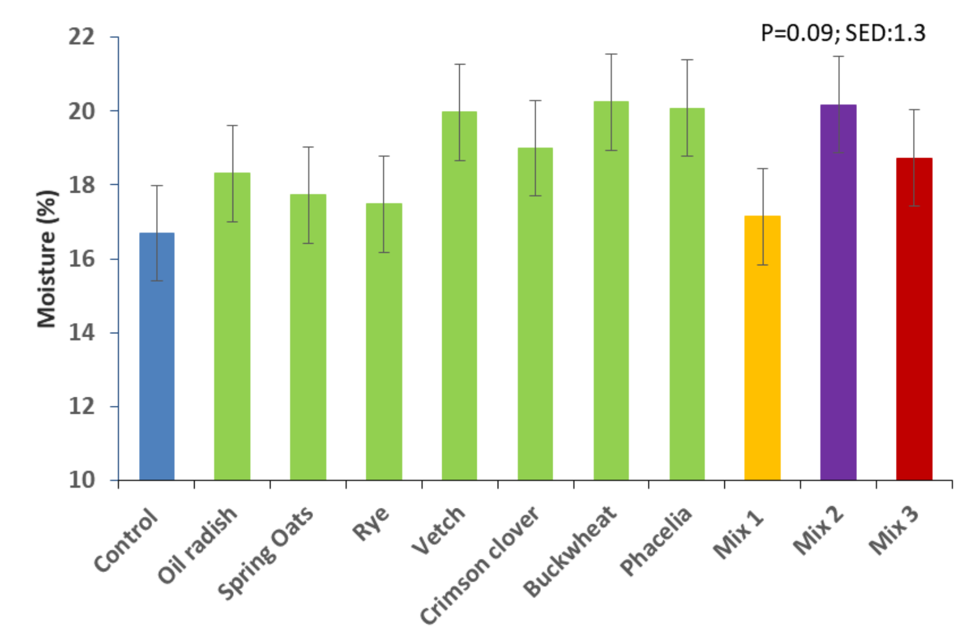


Figure 3-20 Topsoil moisture after cover crop destruction at Kneesall, February 2018

There were very few statistically significant treatment effects on soil properties measured in the winter crop, one year after cover cropping (Table 3.7). Soil structural assessments at Stetchworth suggested that there was some evidence that the highest (i.e. poorest) VESS limiting layer score was associated with the control (no cover crop) treatment (score = 3; 'firm' soil structure) compared to the cover crop treatments which scored 2 – 2.5 ('intact' soil structure). A score of 4 which indicates some compaction, was recorded at both Kneesall and Wilberfoss, although not consistently associated with one particular treatment. Statistically significant differences were only seen with topsoil C:N ratio at Stetchworth, which was highest (9.7) where spring oats or phacelia had been grown and lowest (7.9) where buckwheat had been grown (control had a C:N of 8.8). At both Kneesall and Wilberfoss there were no statistically significant treatment effects and no obvious trend in soil properties across the sites.

Table 3.7 Soil properties (range and statistical significance) measured in the winter crop, approximately 1 year after the cover crop treatments.

Site	VESS 'limiting layer' score	Penetration resistance (Max MPa to 45 cm)	Bulk density (25-30cm); g/cm^3	Worms (No./pit)	SOM (% LOI)	C:N
Stetchworth	2 - 3 NS	2.8 – 3.0 NS	1.15 – 1.37 NS	1 - 7 NS	2.4 – 2.6 NS	7.9 – 9.7 P<0.05
Kneesall	2 - 4 NS	1.7 – 2.1 NS	1.15 -1.23 NS	6 - 13 NS	3.6 -3.9 NS	10 – 10.4 NS
Wilberfoss	3 - 4 NS	4.6 – 5.2 NS	1.28 – 1.35 NS	3 - 8 NS	2.7 – 3.0 NS	9.1 – 12.2 NS

3.2.4. Effect of cover crop treatments on the performance of the following spring and winter crops

NDVI

At each of the sites there were differences in spring barley NDVI values 5 to 6 weeks after drilling (Figure 3-21, Figure 3-22, Figure 3-23). At Stetchworth, the preceding rye, buckwheat and phacelia cover crops resulted in low spring barley NDVI, with the rye treatment NDVI significantly ($P<0.05$) lower than the radish, control, vetch and mix 1 NDVI values. At Kneesall the rye, oats, phacelia and mix 3 treatments resulted in low spring barley NDVI, and again the rye NDVI was statistically significant at the 10% level ($P<0.1$) compared to the other treatments at this site. At the Wilberfoss site, both the vetch and rye cover crops resulted in low spring barley NDVI values, which were significantly lower compared to the other treatments (P<0.001). The phacelia and mix 2 preceding cover crops resulted in the highest spring barley NDVI values at this site, although these were only significantly different to the vetch and rye treatments.

Across all of the sites, the rye preceding cover crop consistently resulted in a relatively low spring barley NDVI value.

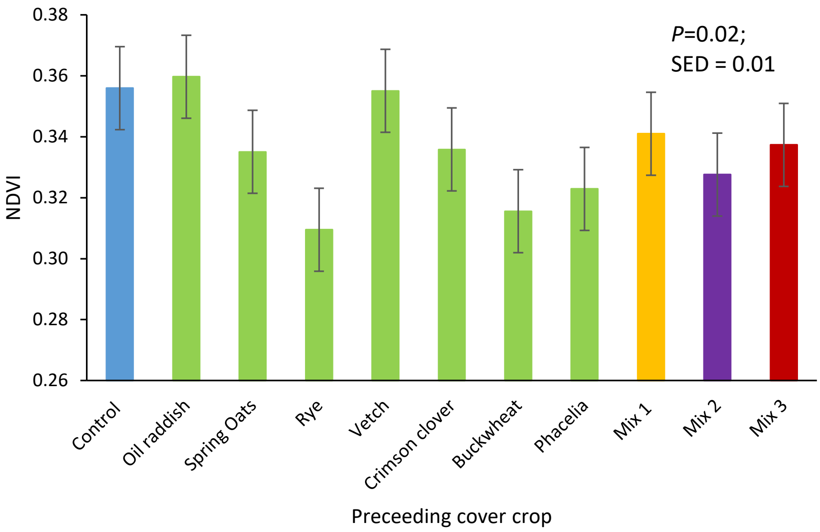


Figure 3-21 Stetchworth spring barley NDVI 6 weeks after drilling on the 26/04/2017.

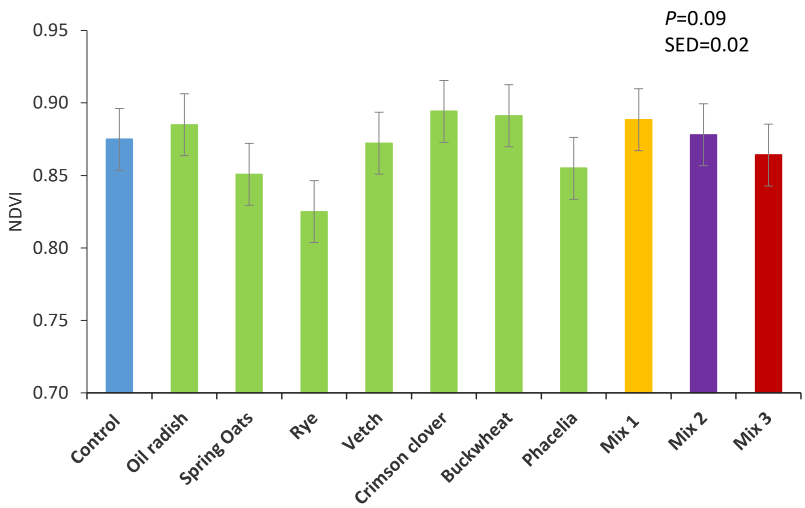


Figure 3-22 Kneesall spring barley NDVI 5 weeks after drilling on 01/06/2018.

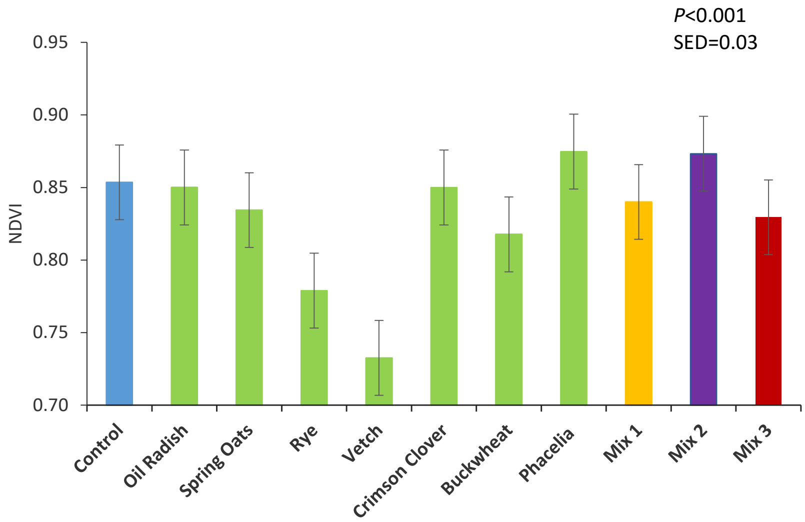


Figure 3-23 Wilberfoss spring barley NDVI 6 weeks after drilling on 31/05/2018

Rooting at anthesis

The lowest spring barley RLD (mean of 1.67 cm/cm^3 Figure 3-24) was measured where spring oats had been grown as a cover crop. This was significantly lower ($F<0.05$) than the spring barley RLDs following the mix 2 cover crop, which had an average of 2.27 cm/cm^3. There was no significant interaction of the treatments with depth. However, in the top 20 cm of the soil profile, the oat and buckwheat cover crops resulted in the lowest spring barley RLDs and mix 2 and rye produced the highest spring barley RLDs. In the 20 – 40 cm soil horizon oats and rye treatments resulted in the lowest spring barley RLDs, whereas clover and phacelia resulted in the highest RLDs. In the 40 – 60cm soil horizon oats and mix 1 resulted in the lowest spring barley RLDs of 0.72 cm/cm^3 and 0.80 cm/cm^3 respectively. Mix 2, clover and buckwheat treatments resulted in the highest spring barley RLDs in the 40 – 60 cm horizon of 1.11 cm/cm^3, 1.10 cm/cm^3 and 1.10 cm/cm^3 respectively.

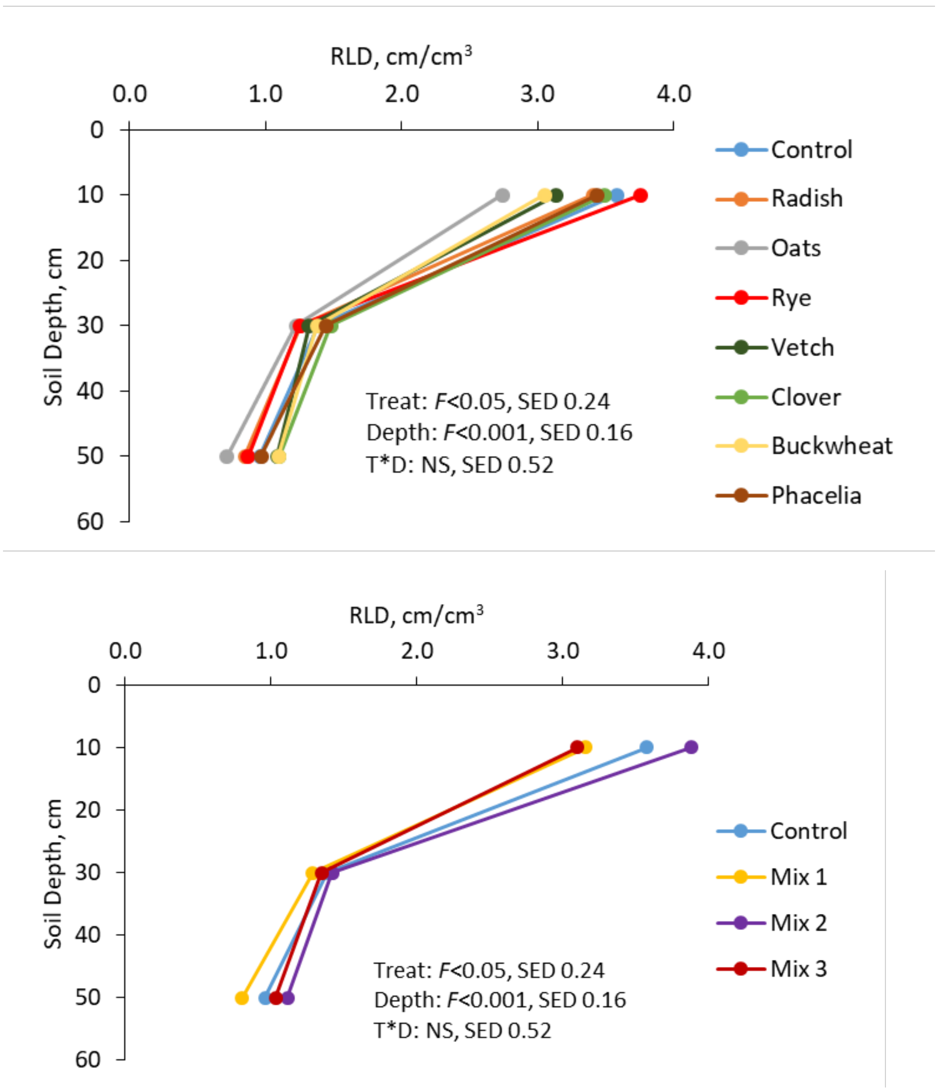


Figure 3-24 Spring barley root length density, cm/cm³ at anthesis. Cross site averages

There were no significant differences between the treatments on spring barley root biomass (Figure 3-25) and as expected root biomass reduced with soil depth (F<0.001). Average spring barley root biomass, over the whole measured soil profile, ranged from 0.11 mg/cm^3 following radish and Mix 3 to 0.138 mg/cm^3 following phacelia. There were also no significant differences in spring barley root diameter between the treatments, the average root diameter was 0.26 mm, but there was a change in diameter with depth (F<0.001): 0.26 mm in the top 0-20 cm, 0.28 mm in the 20-40 cm horizon and 0.26 mm in the 40-60 cm horizon, which was consistent across all treatments.

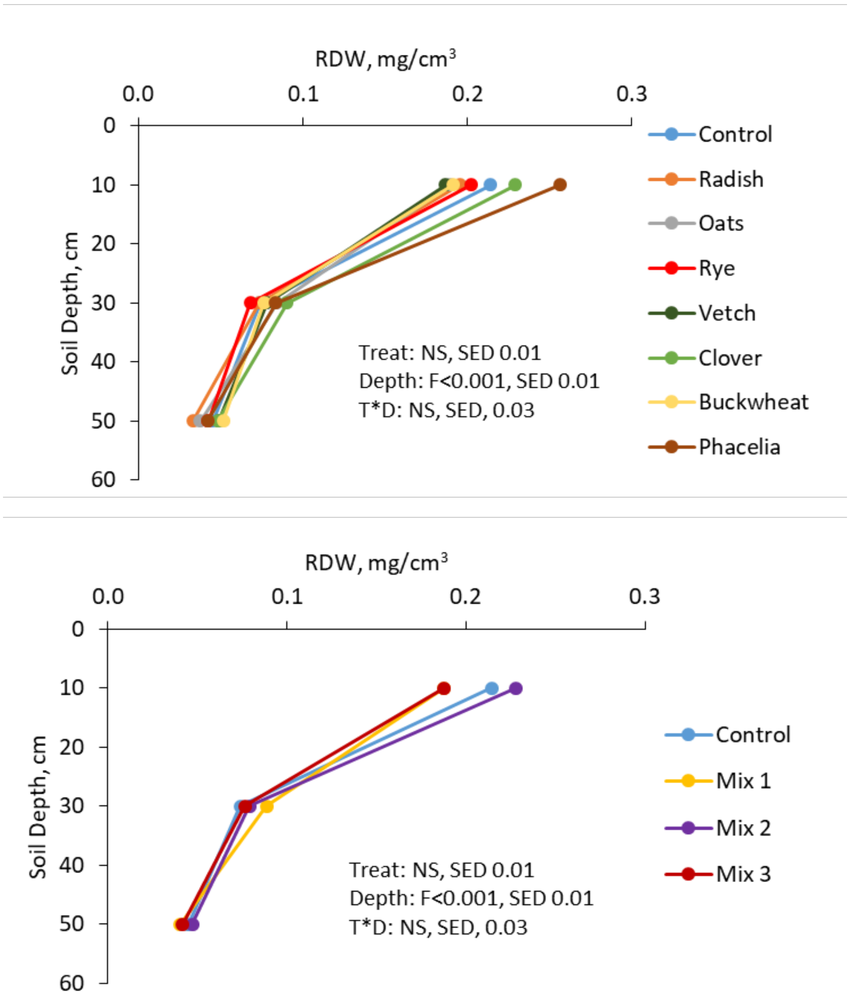


Figure 3-25 Spring barley root biomass (Root dry weight, RDW mg/cm³). Cross site averages.

Specific root length (Figure 3-26) is a measure of the length of root in metres per unit of biomass in grammes. Plants with a high SRL build more root length for a given amount of biomass. The oat cover crop treatment resulted in the lowest average spring barley SRL of 164 m/g (to 60cm depth), which was significantly (F<0.05) lower than that following mix 2 (195 m/g). As would be expected, there was a significant (F<0.001) increase in SRL with depth as roots become thinner towards their ends, with averages of 171, 164 and 224 m/g at 10cm, 30 cm and 50cm, respectively. There was also a significant interaction between treatment and depth, with phacelia, mix 1 and oats giving rise to the lowest spring barley SRL at 10, 30 and 50cm, respectively (F<0.05). There were no significant differences between the treatments in the root lengths in the different diameter classes.

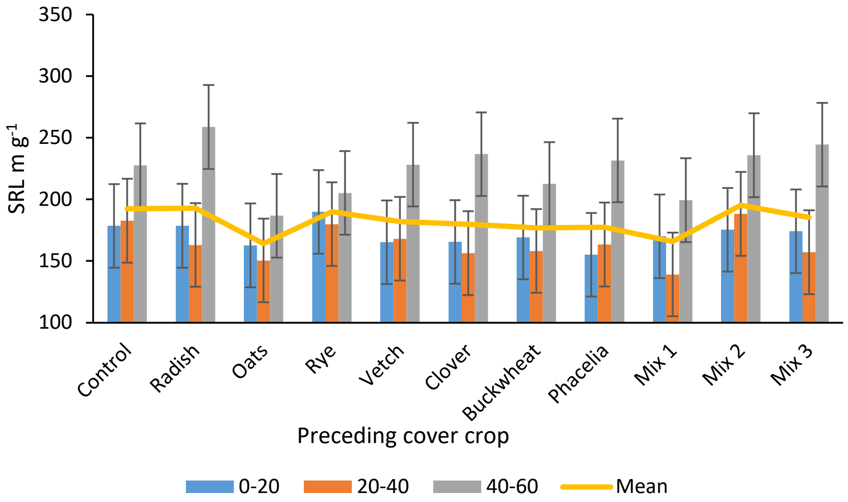


Figure 3-26 Spring barley specific root length (SRL, m/g). Cross site averages.

Spring Barley Yields and Grain N & P

The lowest spring barley yields (Figure 3-27) were measured following the rye and spring oat cover crops, at 5.1 t/ha and 5.2 t/ha, respectively; the control yield was 5.5 t/ha (cross site average data). The highest yields were achieved following oil radish and clover at 5.9 t/ha. Although the cross site analysis wasn't significant, yields following the spring oat cover crop at Kneesall were significantly lower (by up to 2.5 t/ha; $P<0.05$) than those following all but the mix 3 treatment. Yields following the rye cover crop were also significantly lower (by up to 1.8 t/ha) than following the radish and vetch cover crops ($P<0.05$). At Wilberfoss spring barley yields were significantly lower (by up to 1.3 t/ha $P<0.05$) following the rye cover crop compared to the clover, oat, phacelia, mix 1 and mix 2 cover crops. These results reflect the low NDVI and spring barley rooting results measured on the rye and oat cover crop treatments earlier in the season.

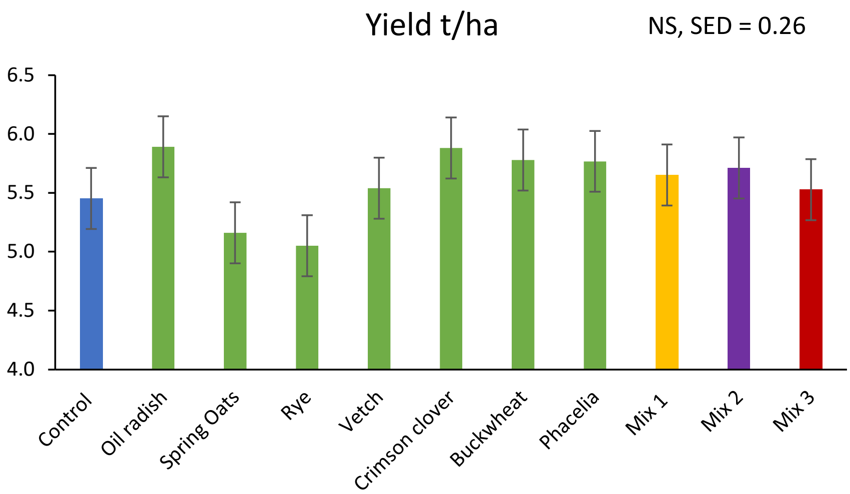


Figure 3-27 Spring barley yields (t/ha @ 85% dry matter). Cross site averages.

There were significant differences (*F*<0.05) in grain N offtake kg/ha between the treatments (Figure 3-28) and differences significant at the 10% level between the grain N content, although the range in grain N content was small (from 1.82% following Mix 2 to 1.88% following radish). Grain N contents were all above the limit for malt distilling (1.65%) and brewing (1.6-1.8%). Grain N offtakes following the rye and oat cover crops were the lowest at 79 kg/ha and 80 kg/ha respectively, reflecting the lower yields. Spring barley grain N offtakes were greatest following clover at 92 kg/ha and were significantly higher (*F*<0.05) than those following the rye and oat cover crops. Grain N offtakes were also high following the radish cover at 91 kg/ha N. The higher grain N offtakes following brassica and legume cover crops may reflect greater soil nitrogen supply compared with the other cover crop treatments.

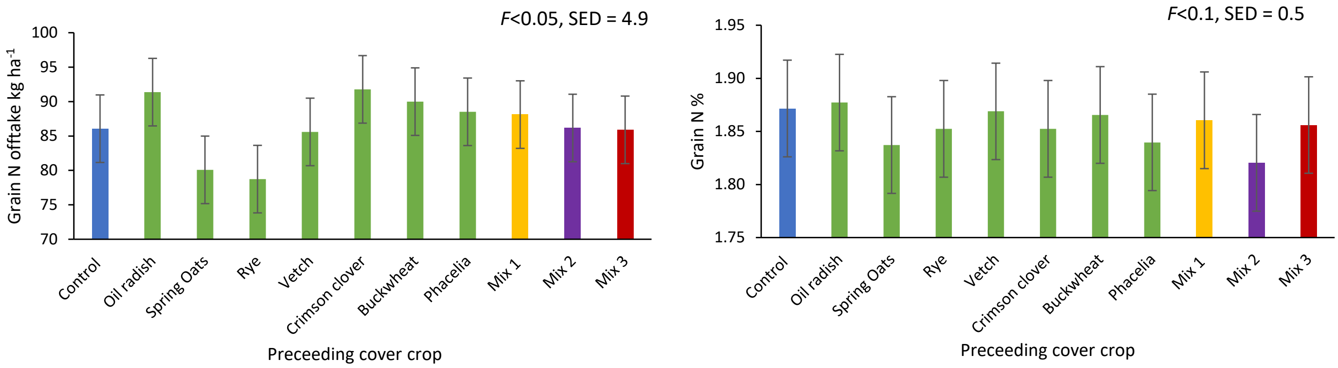


Figure 3-28 Spring barley grain N offtake kg/ha and grain N%. Cross site averages.

Although there were differences in grain N offtake following the different cover crop treatments, there was no difference (*P*>0.05) in post-harvest soil mineral N (to 90cm), total above ground N uptake and therefore N recovered in the crop and soil at harvest (Figure 3-29). The additional N uptake by the cover crop treatments (particularly at Kneesall and Wilberfoss; Table 3.6 & Figure 3-6) could therefore not be detected in the spring barley crop or soil at harvest. The fate of this N is therefore unknown – either it was missed in the measurements undertaken (e.g. root or soil organic N), it has yet to be mineralised, or the rate of mineralisation and uptake was such that the measurements of soil and crop N weren't sensitive enough to detect when and how much N had become available.

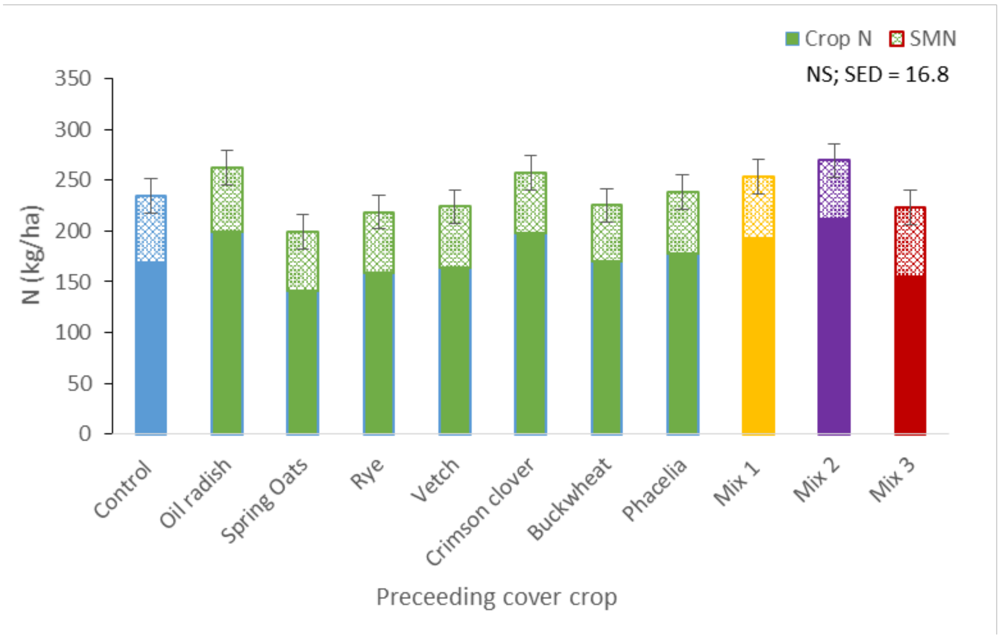
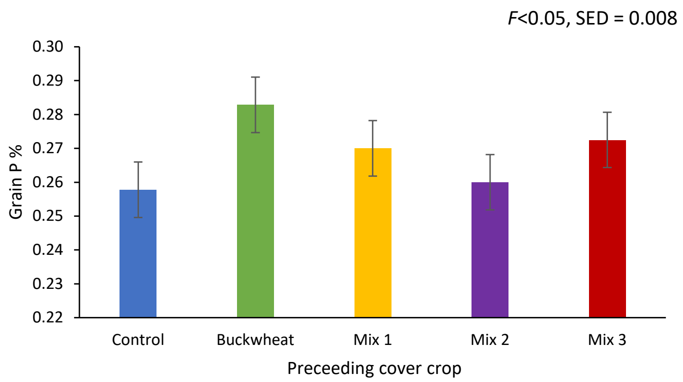


Figure 3-29 Total N recovered in the crop (above ground biomass) and soil (to 90cm) at harvest; cross site averages

Spring barley grain P concentrations were low at all sites and below the recently proposed critical grain P concentration of 0.32% (Sylvester-Bradley et al., 2019). This may be a reflection of the soil P status, which was low at Stetchworth (13 mg/l P; Index 1), although at Kneesall at Wilberfoss a topsoil P index of 2 was measured, suggesting P was not limiting at these two sites (Table 3.1). Grain P concentrations were highest following the buckwheat cover crop (at 0.28%) and were significantly greater (*F*<0.05) than following the control and mix 2 treatments (Figure 3-30). Likewise, spring barley grain P offtake following the buckwheat cover crop was 14.2 kg/ha, which was significantly higher (at the 10% level) than those from mix 2 and the control.



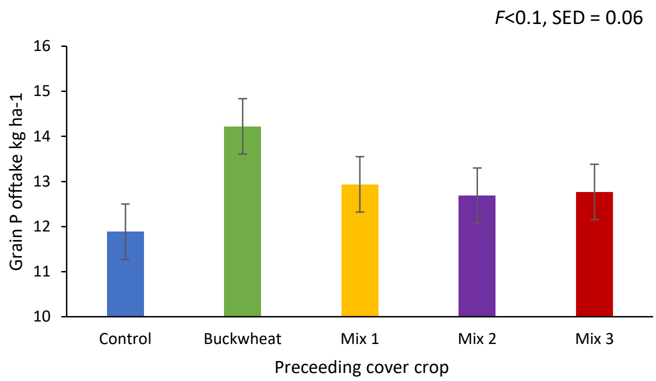


Figure 3-30 Spring barley grain P content (%) and P offtake (kg/ha)). Cross site averages

3.2.5. Cost/benefit analysis

Cumulative margin across the spring and winter crops at Stetchworth, Kneesall and Wilberfoss are shown in Table 3.8, Table 3.9 Table 3.10. A full set of cumulative margin figures for all treatments is provided in Appendix C 11.3.1 - 11.3.3.

At Stetchworth (Table 3.8) the rotation following mix 2 (oil radish/phacelia/buckwheat) resulted in the lowest cumulative margin of £859/ha in part due to poor yield performance in the spring barley, which showed a 0.53 t/ha yield reduction compared to control, equivalent to £72/ha at a spring barley grain price of £135/t. The highest cumulative margin was from either the oil radish or mix 1 (spring oats and crimson clover) at £944/ha. The control cumulative margin was £1033/ha. The cost of establishment of the cover crop ranged from £66/ha (spring oats) to £119/ha (mix 3 - spring oats, crimson clover, oilseed radish, phacelia and buckwheat), which mainly reflected differences in seed costs.

Table 3.8 Cumulative margin for Stetchworth (2017 and 2018)

Treatment	£/ha margin (2017)	£/ha margin (2018)	Cover crop cost £/ha	Cumulative margin £/ha
No cover	191	842	*0*	1033
Oil Radish	132	880	*68*	944
Spring Oats	91	859	*66*	884
Phacelia	139	890	*89*	940
Mix 1	132	908	*96*	944
Mix 2	71	894	*106*	859
Mix 3	149	958	*119*	988
Margins based on spring barley at £135/t ; winter barley at £155/t; nitrogen at 64p/kg N (2017) and 55p/kg N (2018)				
Spring Barley Establishment costs £148/ha; seed costs £77/ha; fertiliser costs at £77/ha and spray costs at £115/ha and harvesting costs £100/ha *Winter Barley* Establishment costs £208/ha; seed costs £70/ha fertiliser costs at £96/ha and spray costs at £169/ha and harvesting costs £100/ha				

At Kneesall (Table 3.9) the spring oats had the lowest cumulative margin of £879/ha due to a yield reduction of 1.43 t/ha compared to control, which may reflect the rotational conflict of growing a cereal after a cereal cover crop. The highest cumulative margin was from the oil radish which was £1256/ha, which reflected the higher spring barley yield and low seed costs compared to the other treatments. The control cumulative margin was £1192/ha. The cost of establishment of the cover crop ranged from £65/ha (spring oats) to £118/ha (mix 3 - spring oats, crimson clover, oilseed radish, phacelia and buckwheat).

Table 3.9 Cumulative margin for Kneesall (2018 and 2019)

Treatment	£/ha margin (2018)	£/ha margin (2019)	Cover crop cost £/ha	Cumulative margin £/ha
No cover	715	478	*0*	1192
Oil Radish	845	478	*67*	1256
Spring Oats	463	481	*65*	879
Phacelia	746	452	*88*	1110
Mix 1	698	452	*95*	1055
Mix 2	785	497	*105*	1177
Mix 3	653	494	*118*	1029
Margins based on spring barley at £175/t; winter oilseed rape at £325t; nitrogen at 55p/kg N (2018) and 59p/kg N (2019)				
Spring Barley Establishment costs at £148/ha; seed costs at £80/ha; fertiliser costs at £77/ha; spray costs at £112/ha and harvesting costs at £100/ha *Winter Oilseed Rape* Establishment costs £230/ha; seed costs £60/ha; fertiliser costs at £100/ha and spray costs at £138/ha and harvesting costs £100/ha				

Only a single season margin (2018) in the spring break was possible to calculate at Wilberfoss (Table 3.10). Following the spring barley the highest cumulative margin was from the spring oats, which was £248/ha. The lowest cumulative margin was from mix 3 (spring oats, crimson clover, oilseed radish, phacelia and buckwheat) which was £124/ha due to the higher cover crop seed cost. The control cumulative margin was £192/ha. The cost of establishment of the cover crop ranged from £109/ha (spring oats) to £162/ha (mix 3 - spring oats, crimson clover, oilseed radish, phacelia and buckwheat).

Table 3.10 Cumulative margin for Wilberfoss (2018 only)

Treatment	£/ha margin (2018)	£/ha margin (2019)	Cover crop cost £/ha	Cumulative margin £/ha
No cover	192	-	*0*	192
Oil Radish	303	-	*111*	193
Spring Oats	357	-	*109*	248
Phacelia	314	-	*132*	182
Mix 1	328	-	*138*	189
Mix 2	349	-	*149*	200
Mix 3	286	-	*162*	124
Margins based on spring barley at £175/t; nitrogen at 55p/kg N (2018)				
Spring Barley Establishment costs at £138/ha; seed costs at £61/ha; fertiliser costs at £77/ha; spray costs at £82/ha and harvesting costs at £100/ha *Following crop* Due to the following crop being sugar beet margins were not possible to be calculated over the two seasons				

3.3. Key messages (large plot experiments)

The large plot experiments have shown:

- Early establishment (August rather than September) is important to maximise the benefits of cover crops, particularly to ensure good crop cover and nutrient recovery.
- In terms of above ground biomass production, radish, buckwheat and mix 2 (which contained these two species) established quickly at all three sites with a high green cover (NDVI) early in the season. However, the rye cover crop produced the greatest amount of above ground biomass by the time of cover crop destruction and had the greatest root length, both early in the season and at destruction; rye also had the widest root diameter. Phacelia roots were slower to develop, but by destruction phacelia had the highest RLD, particularly in the topsoil. Phacelia also produced the narrowest roots and had the highest SRL, suggesting it explored more of the soil for a given root biomass compared to the other cover crop treatments.
- The cereal cover crops tended to have the highest root length densities to depth (60cm), although this was not statistically significant. Buckwheat produced the least root length as measured prior to destruction by frost in November, with the RLD of the remaining volunteers and weeds on this treatment also the lowest at destruction of the other cover crop treatments in February.
- On average the cover crops took up between 30 and 50 kg/ha, although up to 90 kg/ha N was recovered following early establishment of the vetch and clover at the heavier textured site. Highest N recovery was associated with either species that were able to fix additional N (i.e. clover and vetch) or established good above or below ground biomass, early in the season (radish, phacelia and rye). Soil type and moisture were also important factors, with the highest N recovery measured on the heavier textured site (Kneesall 2017-18). At the heavier textured site, nitrogen mineralisation was estimated at *c.* 40 kg/ha (from measurements of SNS on the control treatment) and N fixation was estimated at 20-25 kg/ha on the clover and vetch treatments over the *c.* 6 month period the cover crops were in the ground.
- The additional N uptake by the cover crop treatments (particularly at Kneesall and Wilberfoss) was not detected in the spring barley crop or soil after harvest. The fate of this N is therefore unknown – either it was missed by the measurements undertaken (e.g. root or soil organic N), it had yet to be mineralised, or the rate of mineralisation and uptake was such that the measurements of soil and crop N weren't sensitive enough to detect when and how much N had become available.
- At the heavier textured site, there was some evidence that cover cropping increased topsoil moisture content (0-30cm) at cover crop destruction, although this had no impact on the establishment of spring barley probably due to the *c.* 2 month 'window' between destruction and drilling of the spring crop.
- There was no clear evidence of any improvement in soil structure, organic matter or biological activity (earthworm numbers) following a single year of cover cropping.

- There was little evidence that the performance of the individual cover crop species was improved by including them in a mix. The establishment of green crop cover (NDVI) was most rapid and greatest on the single species treatments compared to the mixes, and although N uptake was greatest on the 5 species mix treatment (phacelia, radish, oats, clover and buckwheat), it was not significantly different to the straight clover treatment. Neither was N uptake by mix 2 (radish, phacelia and buckwheat) significantly different from the straight radish or phacelia treatments. There was also little evidence of enhanced rooting by the species mixes.
- Spring barley establishment (as determined by NDVI) was consistently lower following the rye cover crop at all of the sites, with spring oats also resulting in low NDVI values at two of the sites. Spring barley rooting (RLD and SRL) was also lowest following the oat cover crop, with the highest RLD and SRL measured following mix 2 (this mix had no cereal in it). These differences in establishment and rooting following the two cereal cover crops led to lower yields at harvest and provide robust evidence to support guidance that cereal cover crops (as a single species) should not be grown ahead of a spring cereal cash crop. However, the reason for this is uncertain and it is also uncertain whether the detrimental effect can be negated by using the cereal cover crop in a mix or how much of the mix can be cereal – this appears to be the case for spring oats (83% in mix 1 and 55% in mix 3), although spring barley rooting was 'better' following mix 2 (no cereal). This has implications for the CAP EFA greening rules, which require cover crop mixes to include a cereal and non-cereal.
- There was a trend for a higher spring barley grain phosphorus (P) concentration and grain P offtake where buckwheat had been grown compared to the control treatment (volunteer/weeds). This corroborates evidence in the literature that buckwheat may enhance P availability. However, the mechanism for improved P availability is uncertain, as rooting by the buckwheat and total above ground biomass production was low compared to the other species evaluated.
- There was some increase in cumulative margin following a single year of cover crop, particularly where cover crops were established early (i.e. at Kneesall and Wilberfoss) and seed costs were low (e.g. radish where 2 year margins were increased by up to £64/ha). However, the decline in yields following an oat cover crop resulted in a reduction in cumulative (2 year) margin of between £150/ha and £313/ha compared to the control, and the high seed and establishment costs of some cover crops (particularly the mixes), resulted in a reduction of margins up to £165/ha.

4. Cover Crop Validation Tramline Trials

The replicated plot experiments reported in section 3 have enabled the detailed and robust evaluation of a wide range of cover crop treatments. However, in order to understand the wider implications (particularly from a practical perspective) of using cover crops in the rotation, the use of tramline trials with all operations conducted by the farmer on a field scale, can provide valuable additional information. Validation tramline trials evaluating selected treatments from the large plot experiments were established on four farms: three AHDB monitor farms (in Kent, Yorkshire and Cambridgeshire) and the Hutchinsons Ltd (HLH) demonstration farm (in Cambridgeshire). These trials have been reported as a series of 'case studies' in sections 4.2-4.5 below, but as assessments were similar across all sites a brief outline of the methodologies used is given in section 4.1.

4.1. Methods

Four tramline trials were established, two in autumn 2016 (Kent and Yorkshire) and two in autumn 2017 (Cambridgeshire). Host farmers at each of the sites were asked to pick two of the cover crop mixes used in the replicated plot experiments (Table 3.2, section 3.1.1) to compare with an uncovered control ahead of spring cropping, as part of their normal crop rotation. The treatments were drilled across a full tramline width and length and replicated two or three times across the field, depending on field sizes. At each site, the performance of the cover crop was assessed using satellite imagery of crop cover (NDVI), with cash crop yields (spring and winter crops) determined using yield mapping at the AHDB monitor farms, or from the combine yield meter at the HLH farm. A suite of assessments was conducted on each tramline, including:

- After cover crop destruction (but before spring crop establishment): soil moisture content (to 90cm), penetration resistance (to 45 cm) and bulk density (at 25-30cm depth).
- Spring crop root length (4-5 weeks after drilling; 10 plants per tramline) and final yield.
- Soil penetration resistance (to 45cm), bulk density (at 25-30cm), VESS and earthworm numbers (at three locations per tramline) and topsoil organic matter content in the winter crop (March/April).

The procedure followed for each assessment was the same as for the replicated plot experiments (section 3.1.2 - 3.1.4).

4.2. Kent cover crop validation trial (2016-2018)

This cover crop validation trial was hosted by Mark Bowsher Gibbs at Hempstead Farm (Blackbird Farming) near Sittingbourne in Kent. The trial was established on a loamy soil type (pH 8.1; 3.4% SOM, 24 mg/l ext. P - Index 2; 120 mg/l ext. K - index 1) and compared two different cover crop mixes sown in autumn 2016 ahead of a spring barley crop, with 3 replicate tramlines (30m width) of each treatment (Table 4.1).

The field was raked in late August 2016 and the cover crops drilled on 7th September 2016, using a Sumo (strip tillage) drill, followed by rolling. The surrounding field had a farm cover crop (oats). Satellite imagery at the end of October 2016 (c. 7 weeks after drilling) indicated good crop cover on treatment 3 (mix 3) and a lesser extent treatment 2 (mix 1), with the control having patches of bare soil (Figure 4-1 & Figure 4-2).

Table 4.1 Cover crop treatments at the Kent validation trial site

Treatment	Details
1. Control	Stubble only (no cover crop)
2. Mix 1	Oats (83%) and crimson clover (17%) at 36 kg/ha
3. Mix 3	Spring oats (53%) + Crimson clover (11%) + Oilseed radish (11%) + Phacelia (6%) + Buckwheat (19%) at 37.5 kg/ha

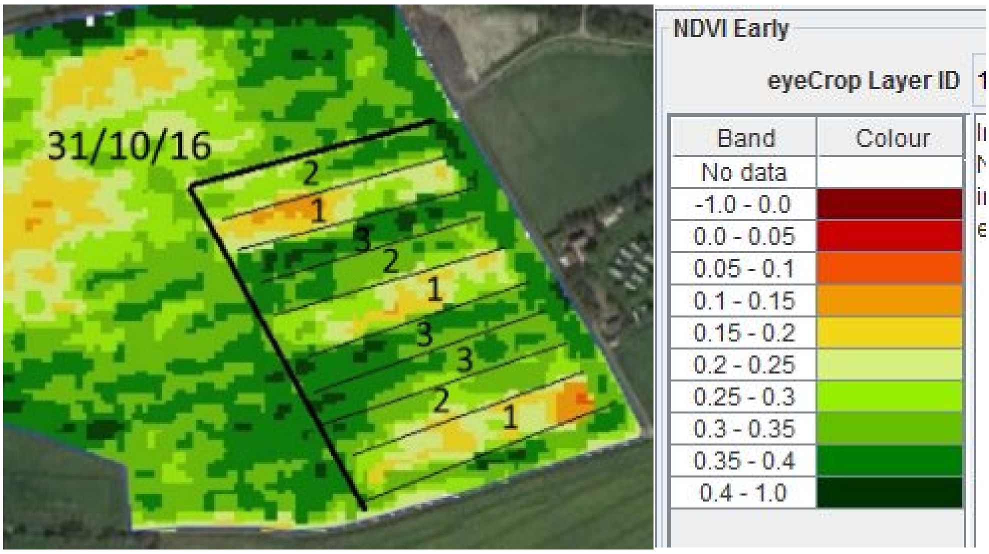


Figure 4-1 Satellite (NDVI) imagery of the trial area in October 2016; NDVI of 1.0 (dark green) indicates full crop cover; NDVI of 0 (red) indicates bare soil.

The cover crops were destroyed using glyphosate on 6/2/17 (the surrounding farm cover crop of oats had been destroyed late 2016 by sheep grazing). Soil penetration resistance tended to be greater on the control treatment (to *c*. 20cm depth) compared to the cover crop treatments at cover crop destruction (Figure 4.3; $P<0.05$ at 14 cm only), but there was no difference in soil moisture content or bulk density.

Control *Mix 1* *Mix 3*

Figure 4-2 Treatment tramlines and crop cover prior to destruction, February 2016

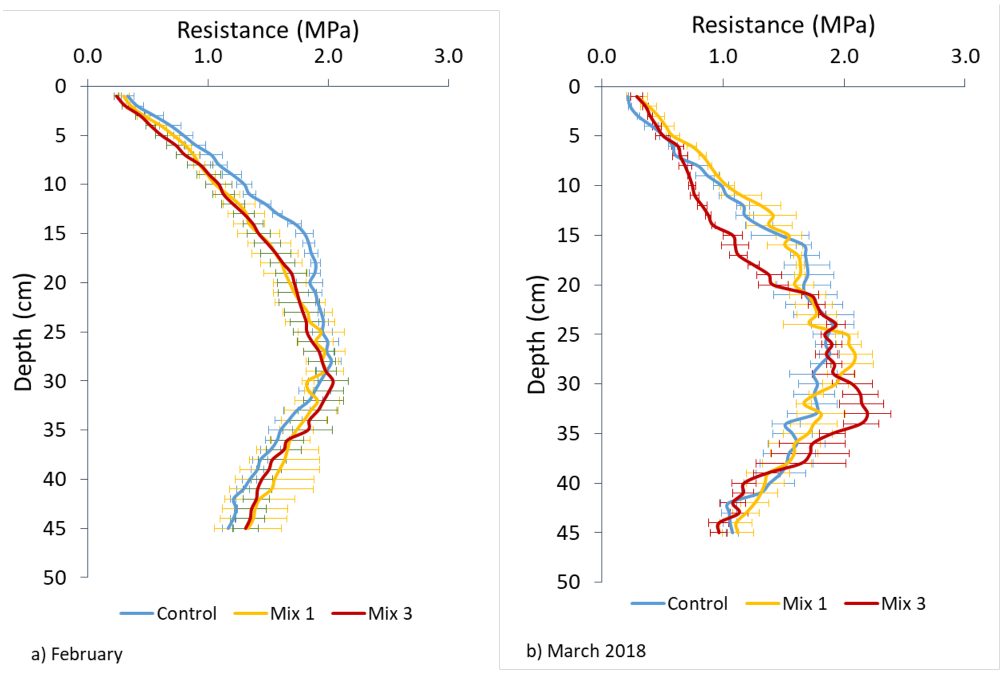


Figure 4-3 Soil penetration resistance in a) February 2017 (cover crop destruction), and b) March 2018 (winter oilseed rape)

4.2.1. Spring barley (2017)

Spring barley (Planet) was direct drilled (Sumo drill) on 23/3/17 and established well, with no differences in early rooting resulting from the previous cover crop treatments. At harvest (2/8/17), the control (no cover crop) treatment had an average yield of 9.35 t/ha (@85% dry matter), according to yield map data. This map was analysed by the Agronomics statistical model in order to ascertain whether any yield differences were a result of the different cover crop treatments or due to other sources of variation such as soil variability across the field (Figure 4-4). Although the modelled effect of the cover crops was to increase yields (by 0.1 t/ha following mix 1 and 0.4 t/ha following mix 3), these differences were more likely due to underlying spatial variation rather than as a result of the cover crop treatments (a yield difference in excess of 0.72-0.76 t/ha would be required in order to have a statistically significant treatment effect at the 95% confidence level; Table 4.2).

Table 4.2 Spring barley yields (2017) as recorded using yield mapping with statistical analysis using Agronomics to predict the effect of the cover crop treatments

Treatment	Mean yield (t/ha @ 85% dm)	Difference in yield from the control treatment t/ha (with 95% confidence limits)
1. Control (stubble)	9.35	
2. Mix 1		+ 0.11 (± 0.72)
3. Mix 3		+ 0.37 (± 0.76)

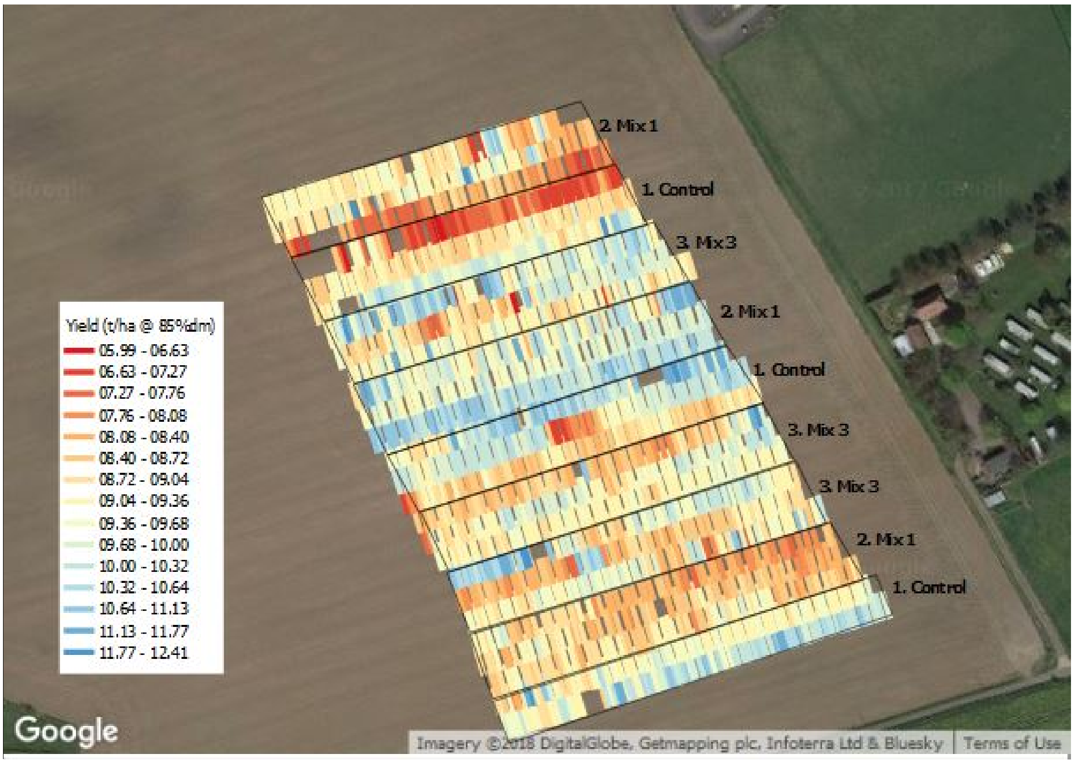


Figure 4-4 Spring barley yield map (August 2017)

4.2.2. Winter oilseed rape (2018)

Winter oilseed rape was drilled in autumn 2017 (29/9/17) and the legacy effect of the previous season's cover crops on soil properties was assessed in spring 2018. There was no effect of the cover crop treatments on topsoil organic matter content, bulk density or visual soil structure (VESS score). However, differences in penetrometer resistance observed in spring 2017 were still apparent in spring 2018 where mix 3 had been grown (Figure 4-3b; $P<0.1$ between 7 and 18cm, and $P<0.05$ at 7, 8, 17 and 18cm). Earthworm numbers were also higher under the cover crop treatments, due to differences in the numbers of juvenile and endogeic (surface dwelling worms) earthworms (Figure 4-5; $P<0.1$).

Table 4.3 Legacy effects of the different cover crop mixes on topsoil properties at Kent site.

Treatment	Bulk density (g/cm^3)[a]	Earthworm count (No/pit)[b]	VESS score ('limiting layer')[c]	Maximum penetration resistance to 30cm (MPa)	SOM content (%)
Control	1.55	4	2	2.0	3.9
Mix 1	1.52	6	2	2.1	3.8
Mix 3	1.58	8	2	2.3	3.8
P[d]	*NS*	*NS*	*NS*	*NS*	*NS*
SED	*0.05*	*0.61*	*0.24*	*0.17*	*0.14*

[a]at 10-15 cm depth
[b]Adults and Juveniles; see Figure 4-5 for detailed breakdown of functional groups
[c]The were two layers – the limiting layer (maximum score) occurred between 10-25 cm depth.
[d]P statistic: NS = not significant.

There was no significant legacy effect of the cover crop treatments on the yield of winter oilseed rape at harvest 2018 (Table 4.4), with an average yield across the whole site of 5.23 t/ha (@ 91% dm) according to yield mapping (Figure 4-6).

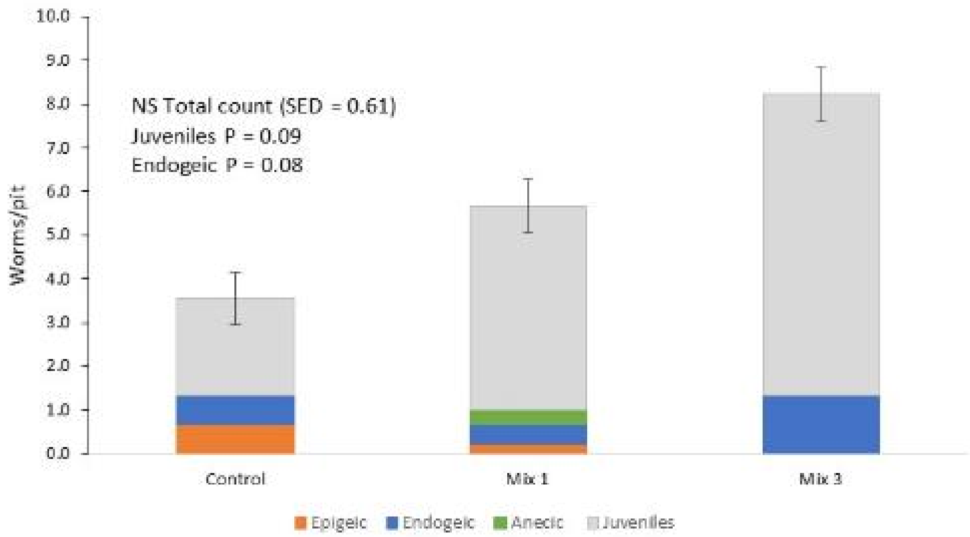


Figure 4-5 Legacy effect of the cover crop treatments on the number of earthworms counted in spring 2018 at the Kent site

Table 4.4. Winter oilseed rape yields (2018) as recorded using yield mapping with statistical analysis using Agronomics to predict the legacy effect of the cover crop treatments

Treatment	Mean yield (t/ha @ 91% dm)	Difference in yield from the control treatment t/ha (with 95% confidence limits)
1. Control (stubble)	5.15	
2. Mix 1		+ 0.15 (± 0.39)
3. Mix 3		+ 0.20 (± 0.39)

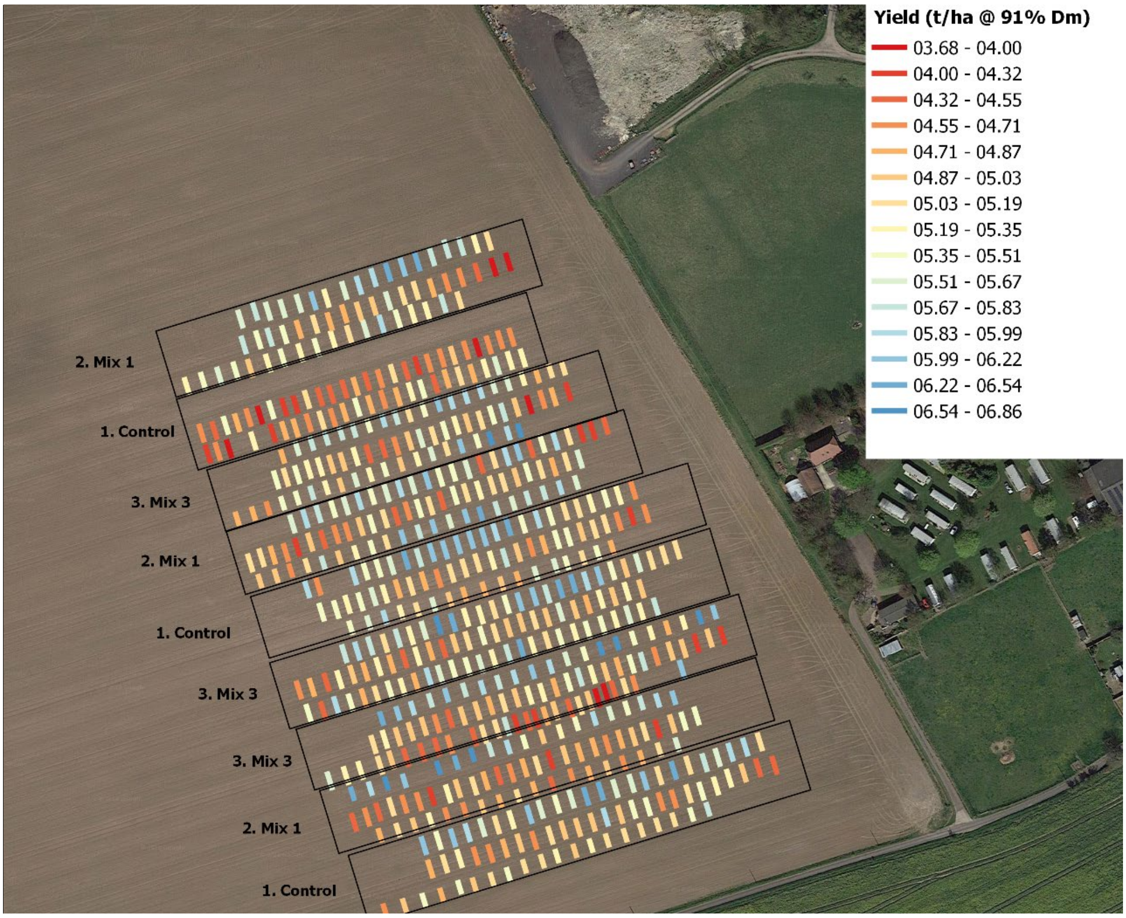


Figure 4-6 Winter oilseed rape yield map (2018)

4.2.3. Cost benefit analysis

Cumulative margins across the spring break and winter crop for the Kent site are shown in Table 4.5. The highest cumulative margin was on the control at £1301/ha, followed by mix 3 (spring oats, crimson clover, oilseed radish, phacelia and buckwheat) at £1275 and mix 1 (spring oats and crimson clover) at £1249/ha. Overall, crop yields were greater following mix 3 and mix 1 than on the control treatment. However, the cover crop costs of £113/ha for mix 1 and £137/ha for mix 3 reduced the cumulative margin by £52/ha and £26/ha, respectively compared to the control.

Table 4.5 Cumulative margin for Kent (2017 and 2018)

Treatment	£/ha margin (2017)	£/ha margin (2018)	Cover crop cost £/ha	Cumulative margin £/ha
Control	672	629	*0*	1301
Mix 1	687	675	*113*	1249
Mix 3	722	690	*137*	1275
Margins based on spring barley at £135/t ; winter oilseed rape at £305/t; nitrogen at 64p/kg N (2017) and 55p/kg N (2018)				
Spring Barley *Establishment costs £133/ha; seed costs £103/ha; fertiliser costs at £108/ha and spray costs at £146/ha and harvesting costs £100/ha* *Winter Oilseed Rape* *Establishment costs £188/ha; seed costs £54/ha fertiliser costs at £154/ha and spray costs at £270/ha and harvesting costs £100/ha*				

4.3. Yorkshire cover crop validation trial (2016-2018)

This cover crop validation trial was hosted by Dave Blacker at New Farm near York. The trial was established on a clay soil (pH 6.0, 5.2% SOM, 20 mg/l ext. P - Index 2; 122 mg/l ext. K - index 2-), and compared two different cover crop mixes sown in autumn 2016 ahead of a spring bean crop, with 2 replicate tramlines (24m width) of each treatment (Table 4.6).

Table 4.6 Treatments at the Yorkshire validation trial

Treatment	Details
1. Control	Stubble only (no cover crop)
2. Mix 1	Oats (83%) and clover (17%) at 36 kg/ha
3. Mix 2	Oil radish (30%), phacelia (20%) and buckwheat (50%) at 20 kg/ha

The cover crops were drilled on 26th August 2016, using a Mzuri strip tillage drill, with the oats (mix 1) drilled using the coulter but the lighter clover seeds broadcast with a slug pellet applicator attached to the drill. Likewise, the radish and buckwheat (mix 2) were drilled with the coulter, but the lighter phacelia seeds broadcast (the control remained as bare stubble). The surrounding field (to the north of the trial) had a farm cover crop mix (clover, oats, phacelia, buckwheat, sunflowers). Satellite imagery at the beginning of November 2016 (c. 10 weeks after drilling) indicated good crop cover on treatment 3 (mix 2), but poorer cover with mix 1, and no cover (bare soil) on the control treatment (Figure 4-7 & Figure 4-8).

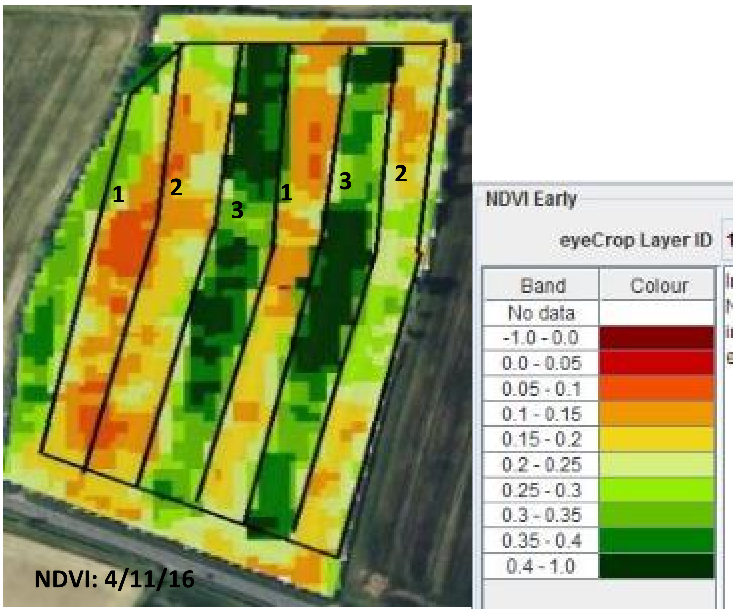


Figure 4-7 Satellite (NDVI) imagery of the trial area in November 2016; NDVI of 1.0 (dark green) indicates full crop cover; NDVI of 0 (red) indicates bare soil.

Control (Oat volunteers) *Mix 1* *Mix 2*

Figure 4-8 Treatment tramlines in November 2016

The cover crops were destroyed using glyphosate on 3/4/17. Topsoil moisture content (0-30cm) was significantly greater (*P*<0.1) and penetration resistance tended to be lower where mix 2 had been grown (although this was not statistically significant; Figure 4-9 a and b), with no difference in topsoil bulk density.

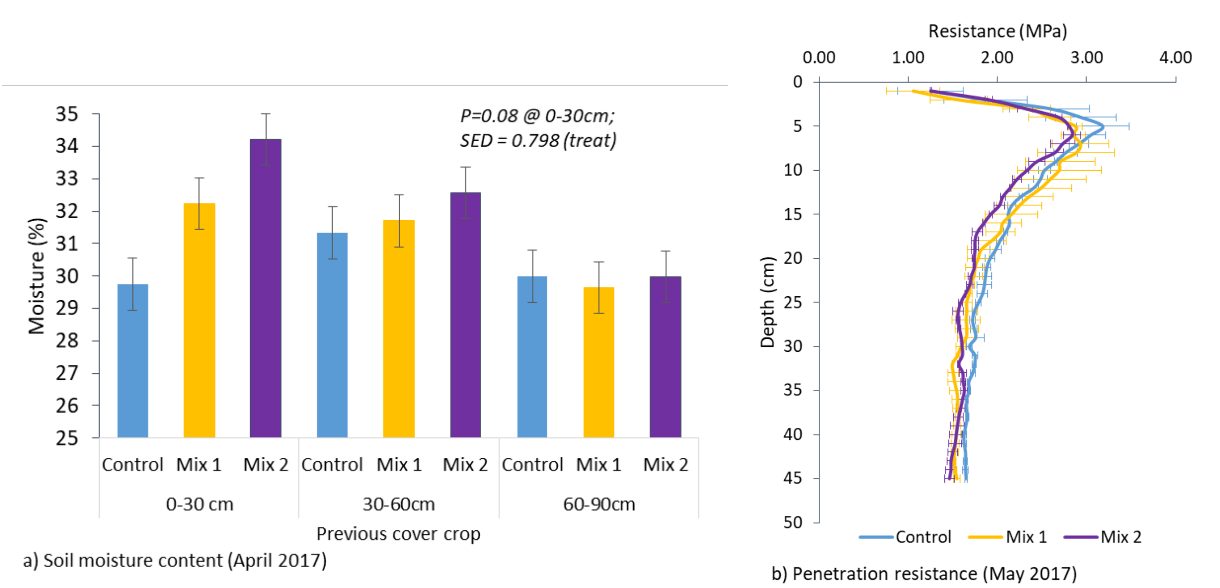


Figure 4-9 Soil conditions in spring 2017

4.3.1. Spring beans (2017)

Spring beans (Vertigo) were strip tilled directly into the stubble 3 days after cover crop destruction (6/4/17). The wetter topsoil following the presence of a cover crop (mix 1 and 2) resulted in poor early rooting by the spring beans where cover crops had been grown (Figure 4-10).

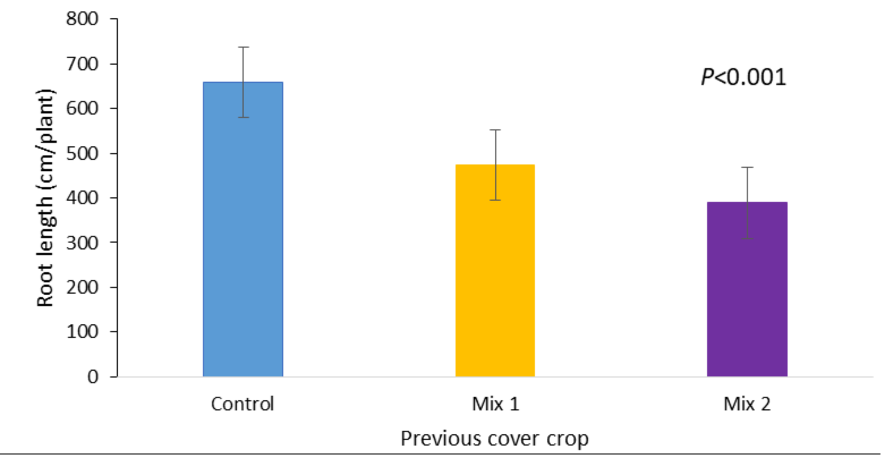


Figure 4-10 Spring bean root length (May 2017)

At harvest, average spring bean yield on the control (no cover crop) treatment was 3.5 t/ha (@85% dry matter), according to yield map data. This map was analysed by the Agronomics statistical model in order to ascertain whether any yield differences were a result of the different cover crop treatments or due to other sources of variation such as soil variability across the field. The modelled effect of both cover crops was to reduce bean yields, but this was only statistically significant following mix 1 (oats and clover) where yields were reduced by 0.4 t/ha (with a yield difference of greater than 0.32 t/ha deemed statistically significant at the 95% confidence level;

Table 4.7 and Figure 4-11). The yield reduction of 0.2 t/ha following mix 2 (oil radish, phacelia and buckwheat) was not statistically significant (at the 95 % confidence level).

Table 4.7. Spring bean yields (2017) as recorded using yield mapping with statistical analysis using Agronomics to predict the effect of the cover crop treatments

Treatment	Mean yield (t/ha @ 86% dm)	Difference in yield from the control treatment t/ha (with 95% confidence limits)
1. Control (stubble)	3.5	
2. Mix 1		-0.36 (± 0.32)
3. Mix 2		-0.20 (± 0.26)

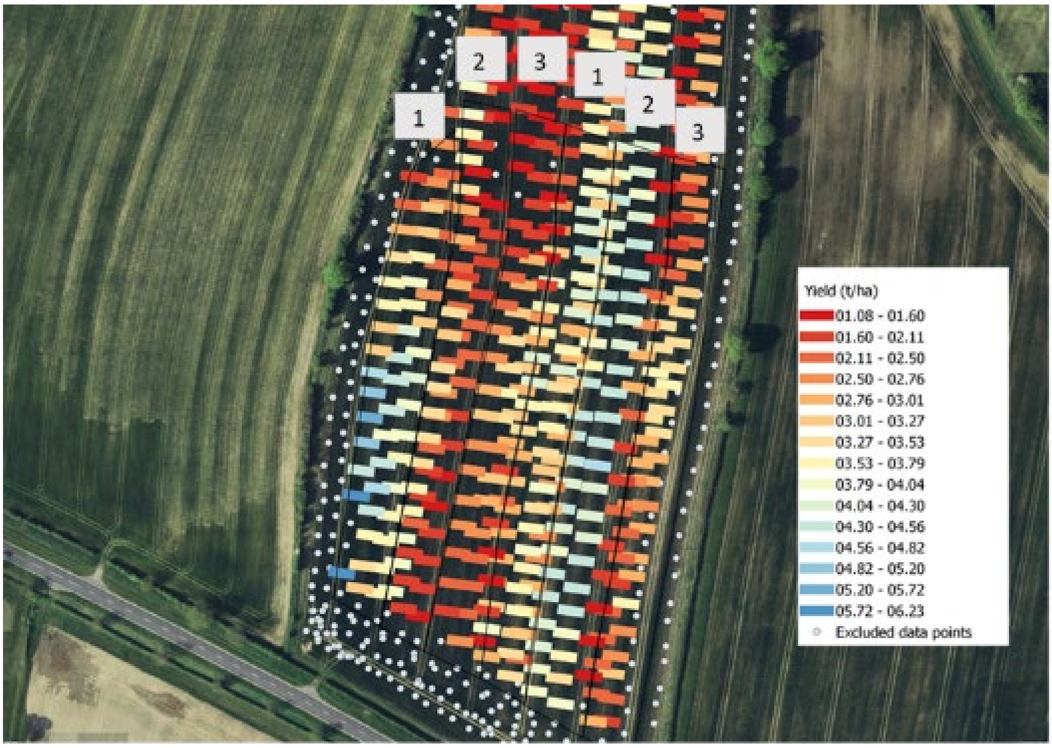


Figure 4-11 Spring bean yield map (2017); see Table 4.6 for details of treatments 1-3.

4.3.2. Winter wheat (2018)

Winter wheat was strip-till drilled into the spring bean stubble in autumn 2017 (25/10/17) and the legacy effect of the previous season's cover crops on soil properties was assessed in spring 2018. There was no effect of the previous cover crop treatments on topsoil organic matter content, bulk density, visual soil structure (VESS score) or earthworm numbers (Table 4.8). There was some suggestion that penetration resistance was lower where mix 2 had been grown, but the results were more variable (and not statistically significant).

Table 4.8 Legacy effects of the different cover crop mixes on topsoil properties at Yorkshire site.

Treatment	Bulk density (g/cm^3)^a	Earthworm count (No/pit)^b	VESS score ('limiting layer')^c	Maximum penetration resistance to 30cm (MPa)	SOM content (%)
Control	1.37	19	3	1.2	5.3
Mix 1	1.35	14	3	1.2	5.7
Mix 2	1.32	19	3	1.1	5.7
P^d	*NS*	*NS*	*N/A*	*NS*	*NS*
SED	*0.86*	*0.40*		*0.06*	*0.62*

[a]at 10-15 cm depth
[b]Adults and Juveniles; > 80% of sample were juvenile & adults were all endogeic species (surface dwellers).
[c]There was no obvious layering of the soil, so the limiting layer score is also the score for the whole of the extracted block (to 25cm) which was the same across the site, so no statistics were possible.
[d]P statistic: NS = not significant.

At harvest 2018 (8/9/18), average winter wheat yield on the control (no cover crop in 2016/17) was 8.3 t/ha (@85% dry matter), according to yield map data, and similar to 2017 the modelled effect of both cover crops was to reduce yields (Table 4.9).

Table 4.9. Winter wheat yields (2018) as recorded using yield mapping with statistical analysis using Agronomics to predict the legacy effect of the cover crop treatments

Treatment	Mean yield (t/ha @ 85% DM)	Difference in yield from the control treatment t/ha (with 95% confidence limits)
1. Control (stubble)	8.3	
2. Mix 1		- 2.1 (± 1.3)
3. Mix 2		- 0.9 (± 1.3)

As was the case in harvest season 2017, the predicted yield reductions were only statistically significant following mix 1 where yields were reduced by *c.* 2 t/ha (with a yield difference of greater than 1.3 t/ha deemed statistically significant at the 95% confidence level; Table 4.9 and Figure 4-12). Although yields were also almost 1 t/ha lower where mix 2 had been grown, this was not predicted to be statistically significant due to underlying spatial variability (Table 4.9).

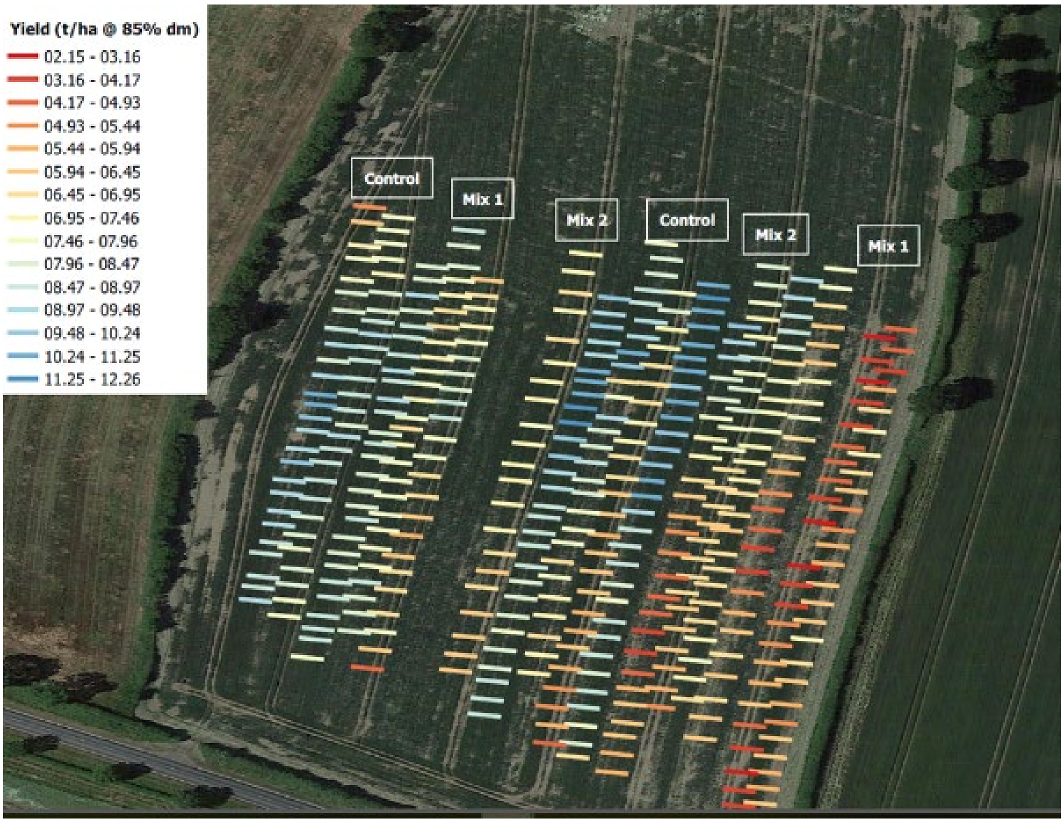


Figure 4-12 Winter wheat yield map (Yorkshire, 2018)

4.3.3. Cost benefit analysis

Cumulative margins across the spring break and winter crop for the Yorkshire site are shown in Table 4.10. The greatest cumulative margin was measured on the control treatment at £943/ha. The cumulative margins on the cover crop treatments were £476/ha lower than the control for mix 1 and £281/ha lower than the control for mix 2.The reduction in cumulative margins on the cover crop treatments reflected the lower cash crop yields in the 2 harvest seasons after the cover crops and the cost of establishing the cover crop treatments (£89/ha for mix 1 and £101/ha for mix 2) .

Table 4.10 Cumulative margin for Yorks. (2017 and 2018)

Treatment	£/ha margin (2017)	£/ha margin (2018)	Cover crop cost £/ha	Cumulative margin £/ha
Control	225	718	*0*	943
Mix 1	163	393	*89*	467
Mix 2	191	572	*101*	662
Margins based on spring beans at £170/t ; winter wheat at £155/t; nitrogen at 64p/kg N (2017) and 55p/kg N (2018)				
Spring Beans *Establishment costs £96/ha; seed costs £64/ha; fertiliser costs at £13/ha and spray costs at £104/ha and harvesting costs £100/ha* *Winter Wheat* *Establishment costs £105/ha; seed costs £73/ha fertiliser costs at £98/ha and spray costs at £193/ha and harvesting costs £100/ha*				

4.4. Cambridgeshire (Old Weston) cover crop validation trial (2017-2019)

This cover crop validation trial was hosted by Russ Mackenzie at Howsons Lodge, Old Weston near Huntingdon. The trial compared two different cover crop mixes sown in autumn 2017 ahead of a spring barley crop, with 2 replicate tramlines (30m width) of each treatment (Table 4.11).

Table 4.11 Treatments at the Cambridgeshire (Old Weston) validations trial site

Treatment	Details
1. Control	Stubble only (no cover crop)
2. Mix 1	Oats (83%) and crimson clover (17%) at 36 kg/ha
3. Mix 3	Spring oats (53%) + Crimson clover (11%) + Oilseed radish (11%) + Phacelia (6%) + Buckwheat (19%) at 37.5 kg/ha

The whole field was raked and the cover crop drilled on the 29th September 2017. Satellite imagery at the end of November 2017 (*c.* 8 weeks after drilling) clearly showed that one side of the field had crop cover, while the other did not, although it is not possible to pick out treatment differences (Figure 4-13). Blackgrass was problematic in the study field (Figure 4-14), so the cover crops were destroyed early using glyphosate in late December 2017. There was no difference in soil moisture, penetration resistance (Figure 4-15) or soil bulk density following cover crop destruction (measured January 2018).

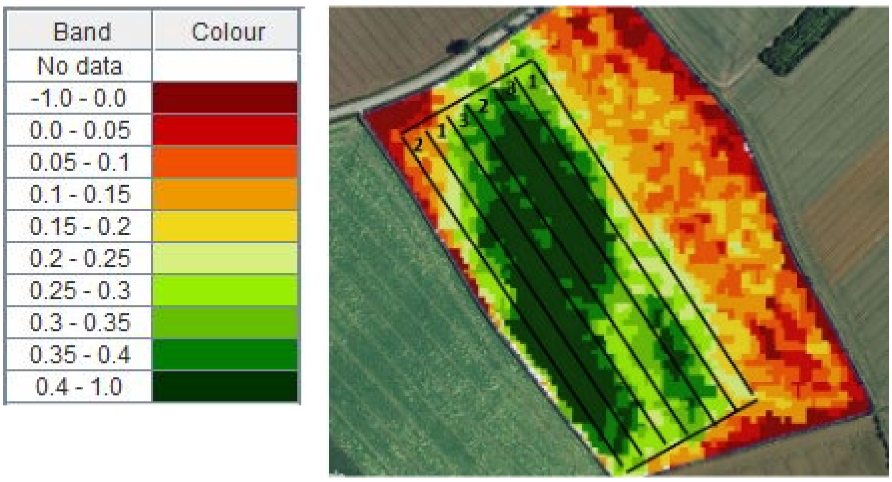


Figure 4-13 Satellite imagery of the trial area showing the approximate position of the treatment tramlines and NDVI on 28th November 2017; NDVI of 1.0 (dark green) indicates full crop cover; NDVI of 0 (red) indicates bare soil.

Mix 1 (with blackgrass & volunteers) Mix 3

Figure 4-14 Treatment tramlines in December 2017

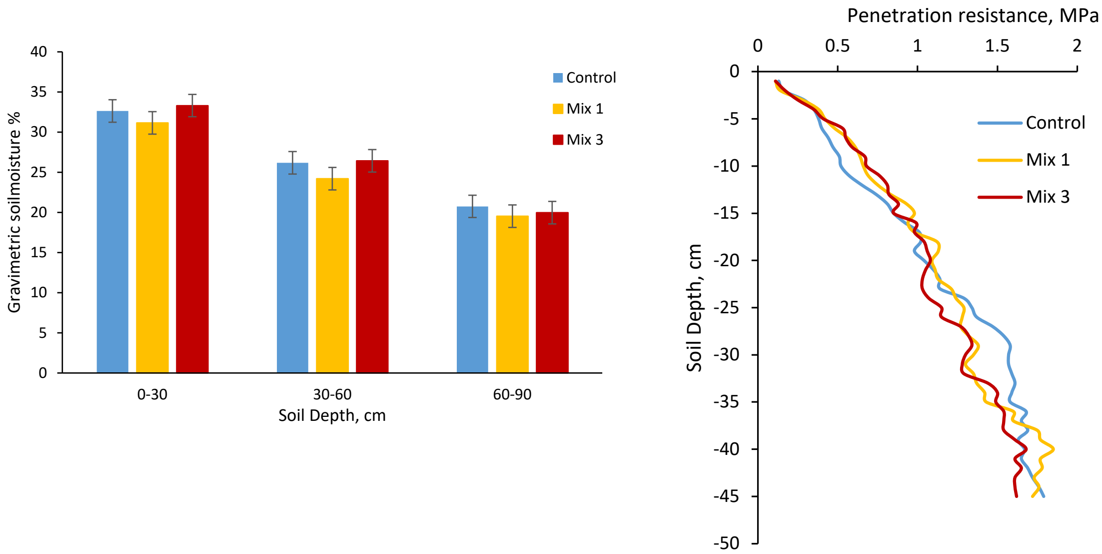


Figure 4-15 Soil conditions in spring 2018 after the cover crops: a) Soil moisture b) Soil strength

4.4.1. Spring barley (2018)

Spring barley was drilled using on 19/4/18 using a Claydon strip till drill followed by rolling. Root measurements showed that there were no impact of the cover crop treatments on spring barley root development.

At harvest (6/8/18) average yield on the control (no cover crop) treatment was 7.1 t/ha (@85% dry matter), according to yield map data. This map was analysed by the Agronomics statistical model in order to ascertain whether any yield differences were a result of the different cover crop treatments or due to other sources of variation such as soil variability across the field. The modelled data suggested that yields following mix 3 were 0.14 t/ha lower than the control however, this difference is more likely due to underlying spatial variation (a yield difference in excess of 0.27 t/ha would be required in order to have a statistically significant treatment effect at the 95% confidence level; Table 4.12 and Figure 4-16). Modelled yield data for mix 1 showed no difference compared to the control.

Table 4.12 Spring barley yields (2018) as recorded using yield mapping with statistical analysis using Agronomics to predict the effect of the cover crop treatments

Treatment	Mean yield (t/ha @ 85% dm)	Difference in yield from the control treatment t/ha (with 95% confidence limits)
1. Control (stubble)	7.14	
2. Mix 1		0.0 (± 0.30)
3. Mix 3		-0.14 (± 0.27)

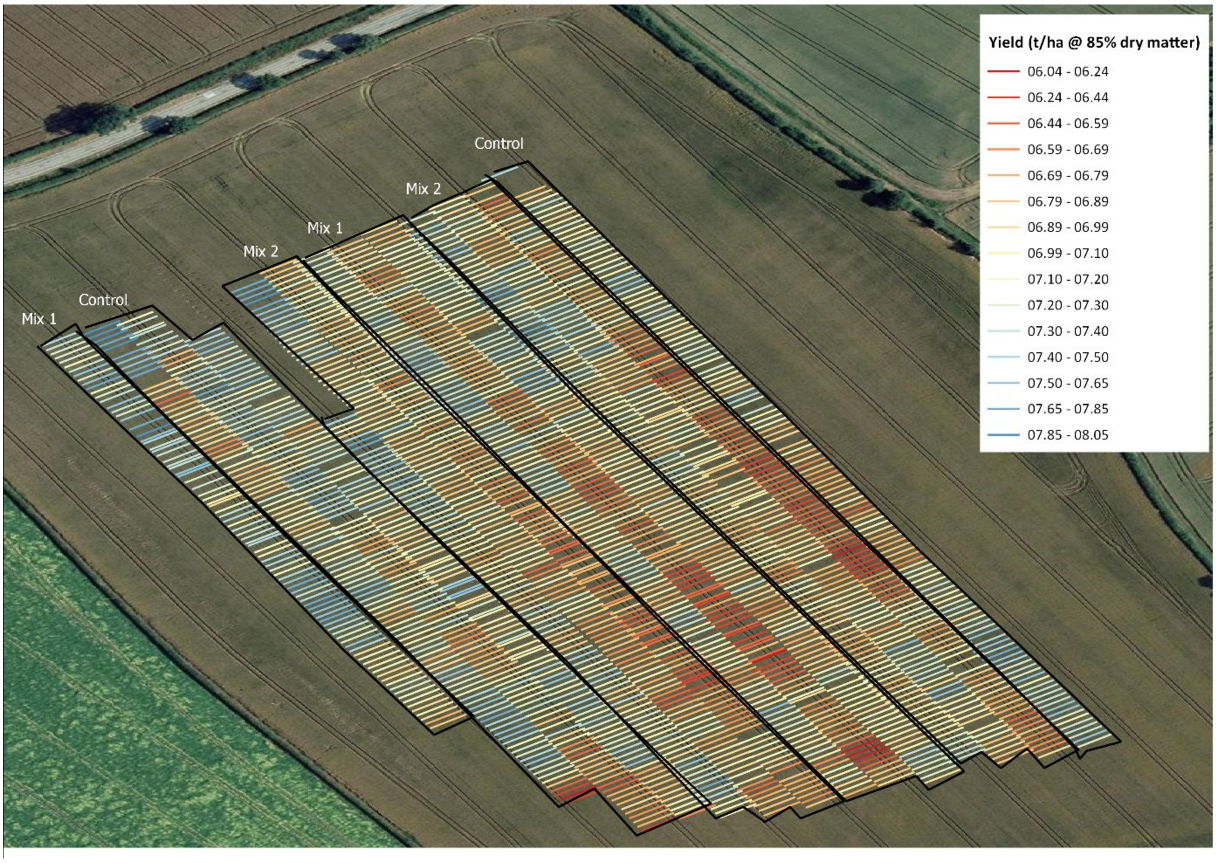


Figure 4-16 Spring barley Yield Map (2018)

4.4.2. Winter beans (2019)

The field was subsoiled in early September 2018 and winter beans (Tundra) drilled on 27/10/18 using a Claydon strip till drill. There was no effect of the previous cover crop treatments on topsoil organic matter content, bulk density, visual soil structure (VESS score) or earthworm numbers measured in April 2019 (Table 4.13). However, the maximum penetration resistance to 30cm was higher following mix 3 (P=0.05). The resistance measurements do not reflect the bulk density and VESS results which, although not statistically significant, suggested lower levels of compaction with mix 3 (Table 4.13). The soils were very dry when sampling was undertaken, which may have been the cause for the higher resistances (rather than compaction).

Table 4.13 Legacy effects of the different cover crop mixes on topsoil properties at the Cambridgeshire Old Weston site.

Treatment	Bulk density (g/cm^3)[a]	Earthworm count (No/pit)[b]	VESS score ('limiting layer')[c]	Maximum penetration resistance to 30cm (MPa)	SOM content (%)
Control	1.47	6	3	1.7	7.0
Mix 1	1.47	7	2	1.6	7.1
Mix 3	1.44	7	2	1.9	7.1
P[d]	*NS*	*NS*	*NS*	*0.05*	*NS*
SED	*0.03*	*1.50*	*0.27*	*0.10*	*0.21*

[a]at 25-30cm depth; [b]Adults and Juveniles; adults were predominately endogeic species (surface dwellers) with no Anecic species recovered (deep dwellers); [c]Two layers were observed in all soil blocks; the limiting layer (maximum score) was observed between 10 and 25 cm depth; [d]P statistic: NS = not significant.

At harvest 2019 (24/8/19), average winter bean yield on the control treatment (no cover crop in 2017/18) was 5.1 t/ha (@96% dry matter), according to yield map data (Table 4.14; Figure 4-17). Whilst average yields were 0.1-0.2 t/ha higher where the cover crops had been grown, the model suggested the differences were probably due to underlying spatial variation rather than as a result of the cover crop treatment (a yield difference in excess of 0.32 t/ha would be required in order to have a statistically significant treatment effect at the 95% confidence level).

Table 4.14 Winter bean yields (2019) as recorded using yield mapping with statistical analysis using Agronomics to predict the legacy effect of the cover crop treatments

Treatment	Mean yield (t/ha @ 86% dm)	Difference in yield from the control treatment t/ha (with 95% confidence limits)
1. Control (stubble)	5.07	
2. Mix 1		+ 0.21 ± 0.35
3. Mix 3		+ 0.17 ± 0.32

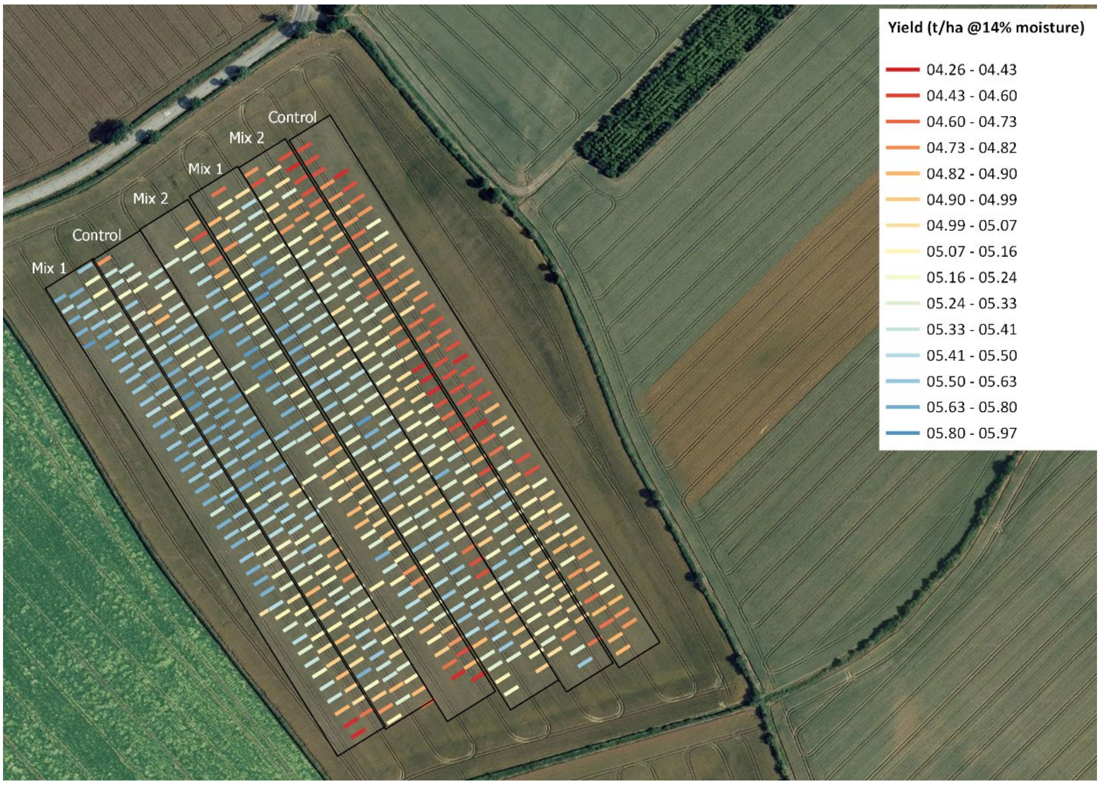


Figure 4-17 Winter bean yield map at Cambridgeshire Old Weston, harvest 2019

4.4.3. Cost benefit analysis

Cumulative margins across the spring break and winter crop for the Cambridgeshire (Old Weston) site are shown in Table 4.15. As was the case at the other 2 study sites, the highest cumulative margin was on the control treatment at £1177/ha, followed by mix 1 (spring oats and crimson clover) at £1105/ha and mix 3 (spring oats, crimson clover, oilseed radish, phacelia and buckwheat) at £1052/ha. The lower margins achieved by the cover crop treatments reflected the cost of cover crop establishment (£105/ha for mix 1 and £128/ha for mix 3).

Table 4.15 Cumulative margin for Cambs – Old Weston (2018 and 2019)

Treatment	£/ha margin (2018)	£/ha margin (2019)	Cover crop cost £/ha	Cumulative margin £/ha
Control	851	326	*0*	1177
Mix 1	851	359	*105*	1105
Mix 3	826	354	*128*	1052
Margins based on spring barley at £175/t ; winter beans at £160/t; nitrogen at 55p/kg N (2018) and 59p/kg N (2019)				
<u>Spring Barley</u> *Establishment costs £95/ha; seed costs £84/ha; fertiliser costs at £66/ha and spray costs at £55/ha and harvesting costs £100/ha* *<u>Winter Beans</u>* *Establishment costs £121/ha; seed costs £88/ha fertiliser costs at £0ha and spray costs at £57ha and harvesting costs £100/ha*				

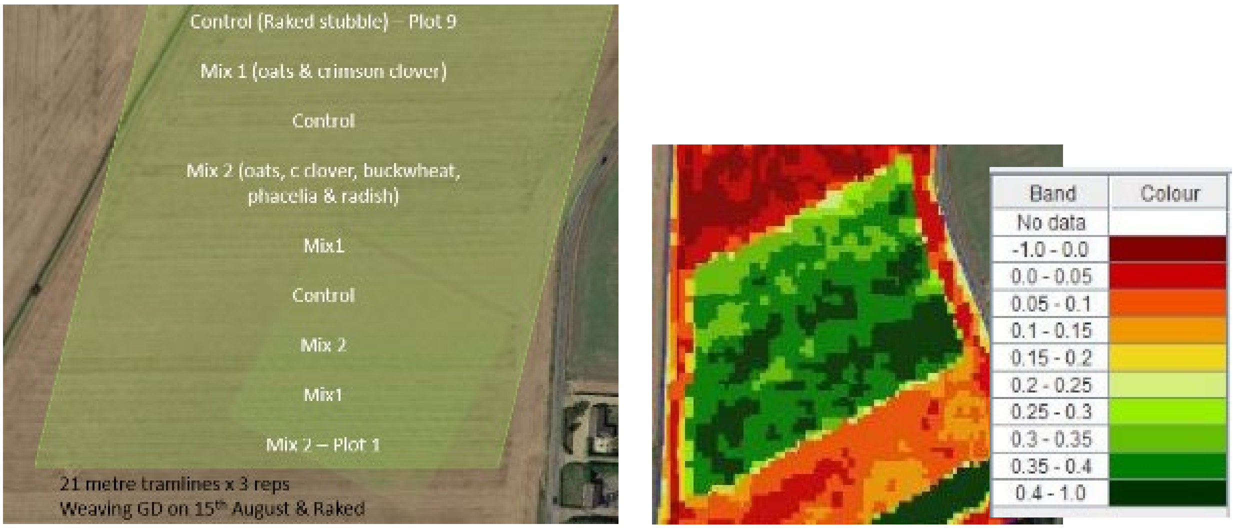
4.5. Cambridgeshire (Benwick) cover crop validation trial (2017-2019)

This cover crop validation trial was hosted by HLH at Marley Farm, near Benwick in Cambridgeshire. The trial was established on a silty clay loam textured soil (pH 8.0; 8.3% SOM, 6.2 mg/l ext. P – Index 0; 209 mg/l ext. K - index 2+) and compared two different cover crop mixes sown in autumn 2016 ahead of a spring barley crop, with 3 replicate tramlines of each treatment (Table 4.16).

Table 4.16. Treatments at the Cambridgeshire (Benwick)

Treatment	Details
1.Control	Stubble only (no cover crop)
2. Mix 1	Oats (83%) and crimson clover (17%) at 36 kg/ha
3. Mix 2	Oil radish (30%), phacelia (20%) and buckwheat (50%) at 20 kg/ha

The field was raked, including the stubble, and the cover crop direct drilled on the 15th of August 2017, using a weaving GD direct drill. Satellite imagery at the end of October 2017 (*c.* 8 weeks after drilling) clearly showed the trial areas (Figure 4-13). The lighter strips to the north of the trial are associated with the control treatment which had low cover of volunteer barley.



a) b)

Figure 4-18 Satellite imagery of the Cambridgeshire-Benwick trial area showing the position of the treatment tramlines (a) and NDVI on 27th October 2017 (b); NDVI of 1.0 (dark green) indicates full crop cover; NDVI of 0 (red) indicates cultivated bare soil around the trial area.

The cover crops were destroyed using glyphosate on 24th February 2018. There was no difference in soil moisture or penetration resistance (Figure 4-19)

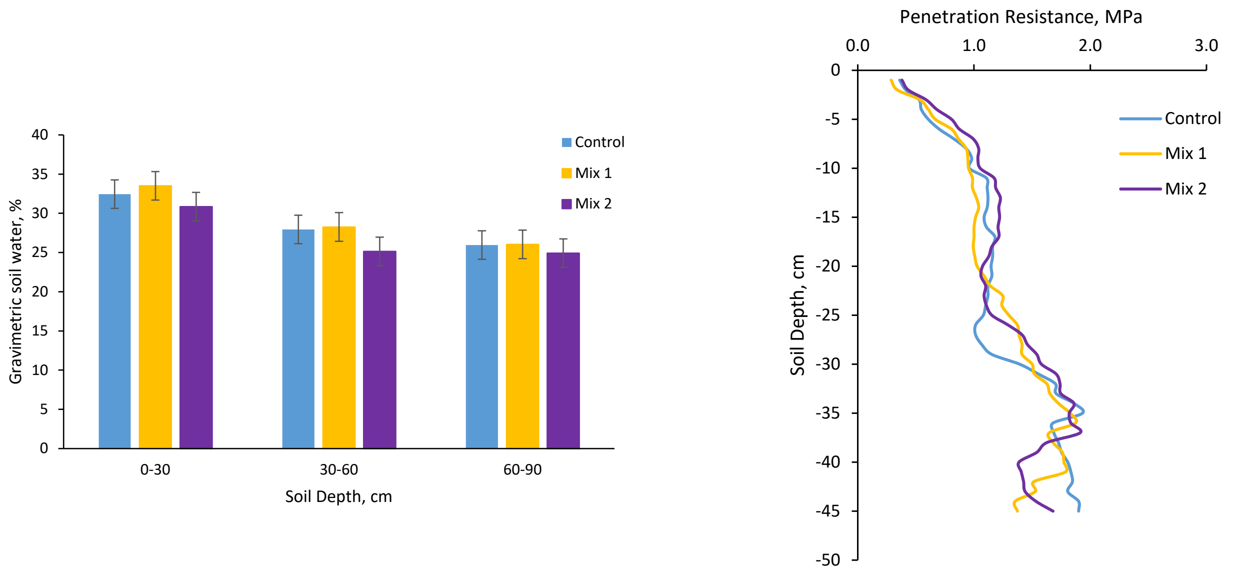


Figure 4-19 Soil moisture content and penetration resistance at cover crop destruction; Cambridgeshire (Benwick) validation trial, Feb. 2018

4.5.1. Spring barley (2018)

Spring barley was direct drilled using a Weaving GD drill with placed Microgranule P fertiliser. At harvest (23/8/2018) average yield on the control treatment was 3.93 t/ha (@85% dry matter). Average yields on both mix 1 and 2 treatments (Table 4.17) at 2.85 t/ha and 2.25 t/ha respectively, were significantly (ANOVA *P*=0.05) lower than on the control.

Table 4.17. Spring barley yields (2018)

Treatment	Mean yield (t/ha @ 85% dm)
1. Control (stubble)	3.93
2. Mix 1	2.85
3. Mix 2	2.25

4.5.2. Winter wheat (2019)

Winter wheat was drilled in autumn on 7th November 2018 using a Weaving GD drill and placed microgranular P fertiliser and the legacy effect of the previous season's cover crops on soil properties assessed in April 2019. There was evidence of compaction at 10-25 cm across the site (VESS limiting layer score of 3-4: 'Firm – compact'), with this being greater where no cover crop had been grown (*P*<0.05; Table 4.18). This was confirmed by the bulk density measured at 25-

30cm on Mix 1, but not mix 2 (P<0.01). There was no difference in winter wheat grain yields at harvest (August 2019) with an average yield of 7.5 ± 0.1 t/ha measured across the trial area.

Table 4.18 Legacy effects of the different cover crop mixes on topsoil properties at the Cambridgeshire Benwick site.

Treatment	Bulk density (g/cm^3)[a]	Earthworm count (No/pit)[b]	VESS score ('limiting layer')[c]	Maximum penetration resistance to 30cm (MPa)	SOM content (%)
Control	1.36	7	4	2.0	8.4
Mix 1	1.30	6	3	1.9	8.8
Mix 2	1.36	6	3	2.0	7.9
P[d]	*<0.01*	*NS*	*<0.05*	*NS*	*NS*
SED	*0.02*	*1.04*	*0.20*	*0.52*	*0.51*

[a]at 25-30cm depth
[b]Adults and Juveniles; c. 70% of sample were juvenile and adults were predominately endogeic species (surface dwellers).
[c]Two layers were observed in all soil blocks; the limiting layer (maximum score) was observed between 10 and 25 cm depth
[d]P statistic: NS = not significant.

4.5.3. Cost benefit analysis

Cumulative margins for the spring barley and winter wheat crops at the Cambridgeshire (Benwick) site are shown in Table 4.19. As was the case at the other sites, the highest cumulative margin was on the control treatment at £825/ha followed by mix 1 (spring oats and crimson clover) at £521/ha (£304/ha reduction) and mix 2 (oil radish, phacelia and buckwheat) at £446/ha (£379/ha reduction). The lower margins calculated for the cover crop treatments reflected the cost of establishment of the cover crops (£119/ha for mix 1 and £129/ha for mix 2) and the lower spring barley yields in the first harvest season after the cover crops.

Table 4.19 Cumulative margin for Cambs - Benwick (2018 and 2019)

Treatment	**£/ha margin (2018)**	**£/ha margin (2019)**	**Cover crop cost £/ha**	**Cumulative margin £/ha**
Control	249	576	*0*	825
Mix 1	64	576	*119*	521
Mix 2	-1	576	*129*	446
Margins based on spring barley at £175/t ; winter wheat at £130/t; nitrogen at 55p/kg N (2018) and 59p/kg N (2019)				
Spring Barley *Establishment costs £97/ha; seed costs £74/ha; fertiliser costs at £91/ha and spray costs at £77/ha and harvesting costs £100/ha* *Winter Wheat* *Establishment costs £140/ha; seed costs £66/ha fertiliser costs at £108/ha and spray costs at £181/ha and harvesting costs £100/ha*				

4.6. Overall evaluation – validation tramline trials

Table 4.20 summarises the key results from the cover crop validation tramline trials. Two of the sites were on heavy soils and two on medium, and therefore compliment the replicated plot sites which tended to be on lighter textured soils. There were two comparisons of mix 1 (two species) with mix 2 (three species, no cereals) on the contrasting soil types, and two comparisons of mix 1 with mix 3 (five species). At three of the sites, all crops (including the cover crops) were established using strip till drills, with a leading cultivation leg followed by a seeding shoe sowing a band of seed. At the Benwick site a low disturbance disc drill was used (Weaving GD), with no prior cultivation. A separate study at this site, managed by HLH on the surrounding field crop, established a cover crop mix using a tined cultivator which moved the soil to 5cm. Where this was done, spring barley yields were markedly higher (up to 4 t/ha higher) than in the trial area, which was attributed to better seed/soil contact where the soil had been disturbed when establishing the cover crop. The host farmer at this site no longer direct drills cover crops as a consequence of these findings (Dick Neale, pers. comm).

On the medium soil type in Kent, there was evidence that the presence of a cover crop, particularly the 5 species mix, improved soil structure (lower penetration resistance) and biological functioning (higher earthworm numbers), but these improvements did not lead to a significant increase in crop yields. This was also the case on the medium soil type in Cambridgeshire, where the level of soil compaction was reduced where cover crops had been grown (again this did not lead to differences in crop yield). However, on a heavy soil type in the north of England, the presence of a cover crop decreased the yield of spring beans. This was a consequence of increased topsoil moisture when the spring beans were drilled on the cover cropped soil, with insufficient time (only 3 days) between cover crop destruction and spring crop establishment to enable the soils to dry. The following winter wheat crop was also reduced where mix 1 had been grown, although there was no evidence that this was due to differences in soil structure (with similar VESS scores and bulk densities across the site).

The impacts of growing cover crops on cumulative margin depended much on the yields of both the spring break after the covers and the following winter crop. At two of the sites, Yorkshire (both in spring beans and winter wheat) and Cambridge, Benwick (spring barley only), significant yield reductions were noted, resulting in the greatest reduction in cumulative margin (>£250/ha). At the two other sites, Kent and Cambridgeshire, Old Weston there were no significant yield reductions and therefore cumulative margins were, in some instances, similar to the control. For example mix 1 at both sites were within £75/ha of the cumulative margin. An increase in yield of 0.25 t/ha in spring barley (based on a grain price of £135/t) and an increase in yield of 0.15 t/ha in oilseed rape (based on a grain price of £305/t) would offset this small loss.

Table 4.20 Overview of the validation cover crop tramline trials. ⇑ indicates an increase in a property/yield; ⇓ indicates a decrease in a property/yield

Farm	Kent	Yorkshire	Cambridgeshire (Old Weston)	Cambridgeshire (Benwick)
Soil texture	Medium	Heavy	Heavy	Medium
Cover crops	Mix 1 & 3	Mix 1 & 2	Mix 1 & 3	Mix 1 & 2
Drilling date & method	7/9/16 Rake & strip till (Sumo)	28/8/16 Strip till (Mzuri)	29/9/17 Rake & strip till (Clayden)	15/8/17 Direct (Weaving GD)
Destruction date & method	6/2/17 Glyphosate	3/4/17 Glyphosate	Late Dec. 2017 Glyphosate	24/2/18 Glyphosate
Spring crop*: Drilling date Harvest date	SBa 23/3/17 2/8/17	SB 6/2/17 3/9/17	SBa 19/4/18 6/8/18	SBa 10/4/18 23/8/18
Winter crop*: Drilling date Harvest date	WOSR 29/9/17 17/7/18	WW 25/10/17 8/9/18	WB 27/10/18 6/8/18	WW 26/10/18 1/9/19
Response: Crop yields	SBa: NS WOSR: NS	Mix 1: SB: 0.4 t/ha ⇓ WW: 2.0 t/ha ⇓	SBa: NS WB: NS	Mix 1 and 2: SBa: 1 - 1.4 t/ha ⇓ WW: NS
Soil properties	Pen. resistance ⇓ and Earthworms ⇑ with mix 3	Topsoil moisture ⇑ with both mixes	No consistent effects	⇓ soil compaction: VESS – mix 1 & 2; Bulk density – mix 1
Cumulative Margin compared to the control (£)	Mix 1: ⇓ (-£52/ha) Mix 3: ⇓ (-£26/ha)	Mix 1: ⇓ (-£476/ha) Mix 2: ⇓ (-£281/ha)	Mix 1: ⇓ (-£72/ha) Mix 3: ⇓ (-£125/ha)	Mix 1: ⇓ (-£304/ha) Mix 2: ⇓ (-£379/ha)

**crops: SBa = Spring Barley; SB = Spring Beans; WOSR = Winter Oilseed Rape; WB = Winter Beans; WW = Winter Wheat*

NS = No statistically significant effect

4.7. Key messages (validations covers)

Field-scale comparisons of the effect of two cover crop mixes compared to a control have shown:

- Some evidence of improved soil structure and biological activity *c.* 12 months after cover cropping (i.e. in the winter cash crop) on the two sites with medium soil textures (lower penetration resistance, bulk density and VESS scores, with higher earthworm numbers recorded at one site).
- Cover cropping on heavier textured soils can be problematic in wet springs. An increase in topsoil moisture where cover crop biomass was high, together with a short window between destruction and spring crop establishment, resulted in a significant spring bean yield decline, with lower yields also recorded in the winter crop where the cover crop mixes had been.

- A single year of cover cropping had no consistent effect on yields of the following cash crop.
- A single year of cover crops resulted in a reduction in cumulative margin. However, in some instances the loss was small, particularly on the lighter textured soils where the risk of soil compaction was low.

5. Cultivation Validation Tramline Trials

A second series of tramline trials was co-ordinated by HLH Ltd in conjunction with Amazone Ltd, to evaluate the performance of cover crops drilled using different crop establishment technologies at the field scale. The trials were conducted at the same four monitor farms used in the validation tramline trials outlined in section 4 above, and have again been reported as a series of 'case studies' (section 5.3 - 5.4).

5.1. Methods

At each site, three different methods of drilling cover crop mix 2 (i.e. oil radish, phacelia and buckwheat, Table 3.2) were evaluated, one of which was the 'farm standard' method, which acted as the control treatment. The treatments were drilled across a full tramline width and length, and where possible treatments were replicated two or three times across the field, depending on field sizes. At each site, measurements were restricted to evaluating the performance of the cover crop using satellite imagery of crop cover (NDVI) and determining cash crop yields (spring and winter crops) using yield mapping at the AHDB monitor farms, or from the combine yield meter at the HLH farm.

5.1.1. Establishment methods

The different cover crop establishment techniques compared high and low disturbance drill types with seeds either 'placed' or 'scattered'. Included in the comparisons were three strip till drills (Sumo DTS , Mzuri Pro-Til and Cousins Microwing), a much lower disturbance tine drill (Amazone Cayena) and a cultivator mounted seeder (Amazone Cenius disc/tine/press cultivator fitted with an Amazone 'green drill' seeder).

The principle of a strip till drill is to cultivate a strip of soil to a variable depth, typically 10-20 cm with a following seeding shoe that sows seed in a 7.5-12.5 cm band followed by press wheels. The soil and crop residue between the cultivated strips is left untouched, with the strips centred at approximately 30cm.

The tine drill (Cayena) is a closer spaced 16 cm row tine drill with narrow (12 mm) tungsten tipped seeding tines. Each tine is proceeded by a wavy cultivation disc to cut residue and loosen soil to 2 cm, with the drilling tine running to *c*. 6 cm depth and seed placed at a depth of *c.* 4 cm via a seeding tube on the back the tine. A following harrow moves loose soil back into the drill slot before a ribbed set of tyres press close the rows. This type of drill moves less soil to depth compared to the strip till drills, but does leave a more evenly cultivated surface (although the 15 cm width of soil between the tines is largely undisturbed).

The cultivator mounted seeder (Amazone 'green drill') can be mounted on any cultivator type, but in this study was mounted to an Amazone Cenius cultivator. The Cenius is a disc + tine or tine only cultivator fitted with a consolidating, depth control press roller. With this, the soil is cultivated to *c*. 6 cm depth and the seed spread immediately in front of the consolidation press, so that it is pressed into the moved soil. This method moves all soil across the working width and seed is placed at more random depths compared to the drilling options.

5.2. Cambridgeshire establishment trials (2016-2018)

At the Cambridgeshire establishment trials, only two methods of cover crop establishment were compared. At the Benwick site the farm standard method for crop establishment was a very low disturbance, direct drill (Weaving GD drill). This was compared with a higher, but localised disturbance, strip till technique (the Cousins micro-wing drill). Drilling was later than planned (mid-September), and conditions were very dry, such that soil penetration with the direct drill was difficult and better establishment was achieved with the strip till drill that enabled better seed to soil contact into moister soil (Dick Neale, pers. comm). At the Old Weston site the farm standard was a strip-till drill (Claydon hybrid drill) and this was again compared to the Cousins Micro-wing strip till drill; with the dry conditions, and a significantly heavier soil type, a low disturbance option was not included in the trial as failure was considered inevitable. Delayed drilling, but predominantly dry conditions, saw very slow growth and poor ground cover at both sites. Dry conditions also meant a very low emergence of black grass prior to sowing the cover crops, but subsequent emergence of a significant population of black grass which swamped the cover crop at both sites by December 2016. Consequently both sites where sprayed off due to the dominance of the black grass and this negated any direct measurable benefit from the cover crop mixtures as the most likely dominant factor would have been the black grass.

Spring barley yields at Benwick were not affected by cover crop establishment methods, and ranged from 6.6 to 8.2 t/ha across the field, with the variation due to underlying spatial variability in soil properties rather than cover crop establishment method. At Old Weston, spring beans were established using two different methods (super-imposed on the different cover crop establishment methods): the Claydon hybrid strip till drill and Amazone tine drill (Cayena). Drilling conditions were good but establishment with the tine drill was disappointing, most likely due to the lack of soil disturbance (and hence seed/soil contact). This led to low plant numbers (visual observation by host farmer) and weed problems at harvest, leading to lower yields across the trial area (2.5 t/ha compared to 3.8 t/ha in the surrounding field, which had no cover crop).

Due to the problems with establishment and blackgrass at these trial sites in the 2016-17 season, the winter crop was not monitored and no cost-benefit analysis was performed.

5.3. Yorkshire establishment trial (2017-2019)

This trial was hosted by Dave Blacker on a sandy loam/clay loam textured soil at New Farm near York. Here cover crop mix 2 was established by direct drilling (Amazone Cayena) or cultivation/broadcast drilling (Amazone Greendrill on a compact disc harrow) and compared with the farm standard Mzuri strip till drill (Table 5.1 and Figure 5-1), with 3 replicate tramlines of each treatment. Crop residues from the previous crop were chopped and the cover crops drilled into the stubbles on 22nd August 2017; 36 mm rainfall occurred the day after drilling.

Table 5.1 Cover crop establishment methods at the Yorkshire trial site

Treatment	Details
1.Direct drill	Amazone Cayena tine seeder; shallow drill with minimal soil disturbance; no pre-cultivation
2.Cultivator/broadcast drill	Amazone GreenDrill on Certos heavy compact disc harrow; two rows of discs cultivating to 8cm depth with seed blown onto the surface followed by rolling
3.Farm standard –Strip till	Mzuri; a deep tine cultivates a strip of ground to about 15cm depth ahead of the seed coulter

1.

2.

3.

Figure 5-1 Drills used to establish the cover crop mix at the Yorkshire site.

1. *Amazone Cayena tine seeder*
2. *Amazone GreenDrill*
3. *Mzuri strip till drill*

Satellite imagery at the beginning of December 2017 (*c*. 3 months after drilling) indicated some areas of poorer vegetation cover, particularly associated with the cover crop established using the direct drill (Figure 5-2). The cover crops were destroyed using glyphosate on 24/3/2018.

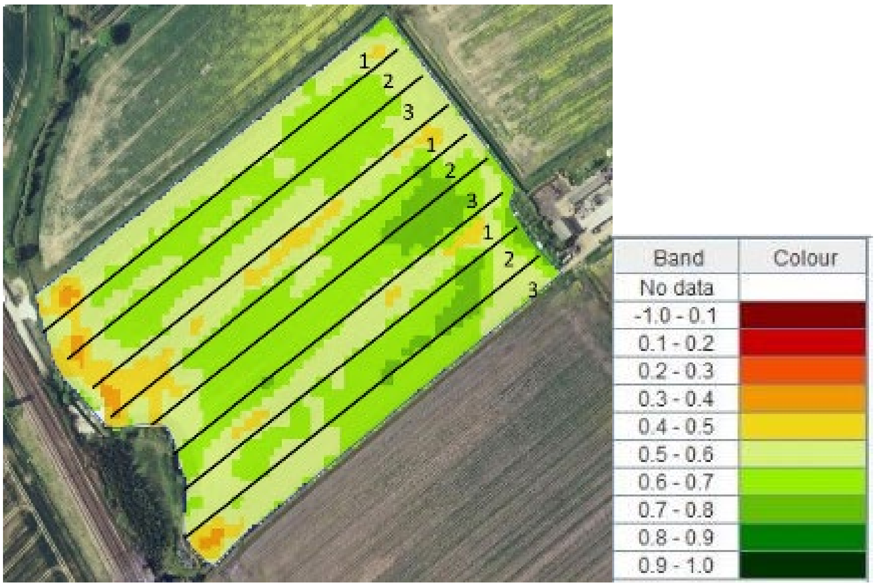


Figure 5-2 Satellite imagery of the trial area showing the approximate position of the treatment tramlines (see Table 5.1 for key) and NDVI on 8th December 2017; NDVI of 1.0 (dark green) indicates full crop cover; NDVI of 0 (red) indicates bare soil.

5.3.1. Spring beans (2018)

Spring beans were drilled using the Mzuri strip till drill on 23/4/2018 *c.* 1 month after cover crop destruction and harvested on 2/9/18 using a yield mapping combine (Figure 5-3). According to analysis of the yield map using the Agronomics statistical model, the average yield following the Mzuri strip till cover crop tramline (Mzuri) was 2.8 t/ha (@85% dry matter). This model aims to predict whether any yield differences observed are a result of the different cover crop establishment methods or due to other sources of variation such as soil variability across the field. The model predicted that where the cover crop was drilled using the GreenDrill (cultivator drill) spring bean yields were *c*. 0.36 t/ha higher and where the Cayena (direct drill) had been used to establish the cover crop, spring bean yields were 0.55 t/ha higher than where the Mzuri had been used (Table 5.2), with a yield difference greater than 0.27-0.29 t/ha deemed statistically significant at the 95% confidence level. This suggests that where there had been greater cover crop biomass (which from the satellite imagery – and confirmed by the host farmer - was where the Mzuri drill had been used; Figure 5-2), spring bean yields were lower.

Table 5.2 Spring bean yields as recorded using yield mapping with statistical analysis using Agronomics to predict the effect of the cover crop treatments

Cover crop establishment method	Mean yield (t/ha @ 85% dm)	Difference in yield from the Mzuri treatment t/ha (with 95% confidence limits)
1. Mzuri strip till drill	2.8	
2. GreenDrill cultivator		+ 0.36 (± 0.27)
3. Cayena direct drill		+ 0.55 (± 0.29)

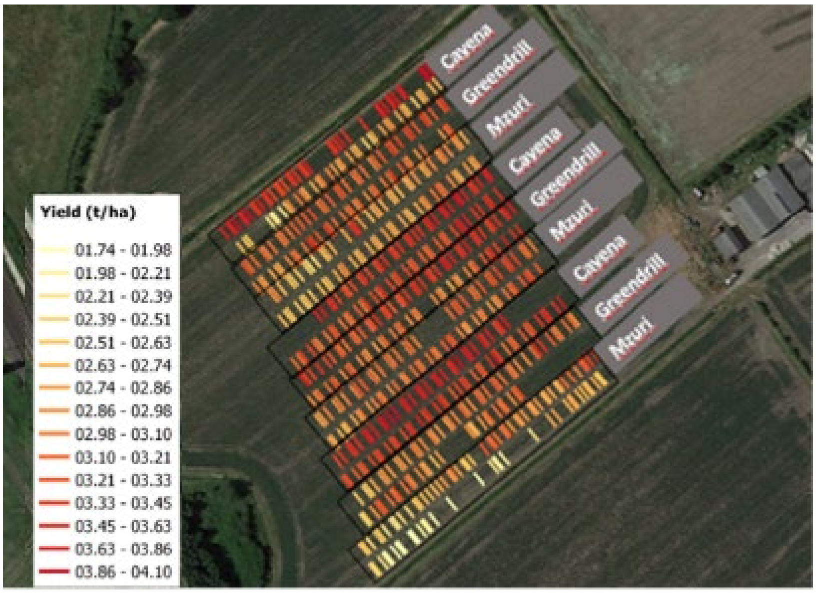


Figure 5-3 Spring bean yield map (August 2018)

5.3.2. Winter wheat (2019)

The field was subsoiled and winter wheat drilled using the Mzuri strip till drill on 8/10/19 and harvested on 15/8/19. Unfortunately the yield map was not of sufficient quality to be analysed using the Agronomics statistical software, so only the overall yield for the whole field could be reported. This ranged from 4 (on the headlands and end of the combine runs) to 14 t/ha, with an average yield of 11.9 t/ha and standard deviation of 1.1 t/ha.

5.3.3. Cost benefit analysis

Cumulative margin across the spring bean and winter wheat crops grown at the Yorkshire site are shown in Table 5.3. The lowest cumulative margin of £644/ha was on the Mzuri drill (Farm Standard) treatment and the highest cumulative margin at £746/ha was on the Amazone Cayena drill treatment. The cost of the cover crop was £134-139/ha, depending on the method of establishment.

Table 5.3: Cumulative margin for Yorks (2018 and 2019)

Treatment	£/ha margin (2018)	£/ha margin (2019)	Cover crop cost £/ha	Cumulative margin £/ha
Amazone Cayena	195	684	*134*	746
Amazone GreenDrill	160	684	*139*	705
Mzuri	93	684	*134*	644
Margins based on spring beans at £185/t ; winter wheat at £130/t; nitrogen at 55p/kg N (2018) and 59p/kg N (2019)				
Spring Beans *Establishment costs £89/ha; seed costs £119/ha; fertiliser costs at £0/ha and spray costs at £125/ha and harvesting costs £100/ha* *Winter Wheat* *Establishment costs £168/ha; seed costs £71/ha fertiliser costs at £127/ha and spray costs at £223/ha and harvesting costs £100/ha*				

5.4. Kent establishment trial (2017-2019)

This trial was hosted by Mark Bowsher Gibbs on a loam textured soil at Hempstead Farm in Kent. Here, as in Yorkshire, cover crop mix 2 was established by direct drilling (Amazone Cayena) or cultivation/broadcast drilling (Amazone Greendrill on a compact disc harrow) and compared with Mark's farm standard Sumo DTS strip till drill (Table 5.4 and Figure 5-4), with just a single tramline of each treatment. The field was raked in late August and the cover crops drilled into the stubbles on 5th September 2017. The cover crops were destroyed using glyphosate on 8/2/18.

Table 5.4 Cover crop establishment methods at the Kent trial site

Treatment	Details
1. Direct drill	Amazone Cayena tine seeder; shallow drill with minimal soil disturbance; no pre-cultivation
2.Cultivator/broadcast drill	Amazone GreenDrill on Certos heavy compact disc harrow; two rows of discs cultivating to 8cm depth with seed blown onto the surface followed by rolling
3.Farm standard – Strip tillage	Sumo DTS; cultivation tine set to work at *c.* 15cm

1.

2.

3.

Figure 5-4 Drills used to establish the cover crop mix in Kent

1. *Amazone Cayena tine seeder*
2. *Amazone GreenDrill*
3. *Sumo DTS strip till drill*

Satellite imagery at the end of November 2017 (*c.* 10 weeks after drilling) indicated some areas of poor vegetation cover, but this did not seem to be treatment-related, rather a result of underlying spatial variability, with the north-east of the field having better crop cover than the south-west part. (Figure 5-5).

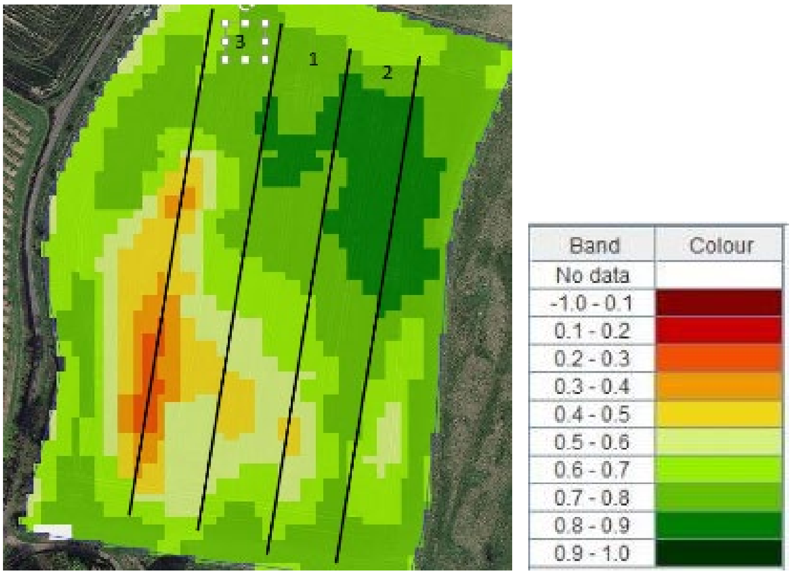


Figure 5-5 Satellite imagery of the trial area showing the approximate position of the treatment tramlines (see Table 5.4 for key) and NDVI on 25th November 2017; NDVI of 1.0 (dark green) indicates full crop cover; NDVI of 0 (red) indicates bare soil.

5.4.1. Spring barley (2018)

The site was raked and spring barley (Planet) direct drilled (Sumo drill) on 24/3/18 and harvested on 7/8/18 using a yield mapping combine (Figure 5-6). According to analysis of the yield map using the Agronomics statistical model, the average yield following the direct drilled cover crop tramline (Cayena) was 7.6 t/ha (@85% dry matter). This model aims to predict whether any yield differences observed are a result of the different cover crop establishment methods or due to other sources of variation such as soil variability across the field. The model predicted that where the cover crop was drilled using the GreenDrill (cultivator drill) spring barley grain yields were c. 1.5 t/ha higher (statistically significant at the 90% level of confidence or P<0.1), but where strip tillage (Sumo DTS) had been used to establish the cover crop, spring barley yields were almost 2 t/ha lower (P<0.05; Table 5.5). The poor cover crop establishment observed from the satellite imagery was concentrated in the south-western corner was where the strip till drill had been used (Figure 5-5), and although the statistical software aims to account for underlying spatial variability, the differences in spring barley yield are thought to be due to inherent variation in the soil rather than a result of poor cover crop performance.

Table 5.5. Spring barley yields as recorded using yield mapping with statistical analysis using Agronomics to predict the effect of the cover crop treatments

Cover crop establishment method	Mean yield (t/ha @ 85% dm)	Difference in yield from the Cayena treatment t/ha (with 95% confidence limits)
1. Cayena direct drill	7.63	
2. GreenDrill cultivator		+ 1.46 (± 1.96)
3. Sumo DTS strip tillage		-1.99 (± 1.91)

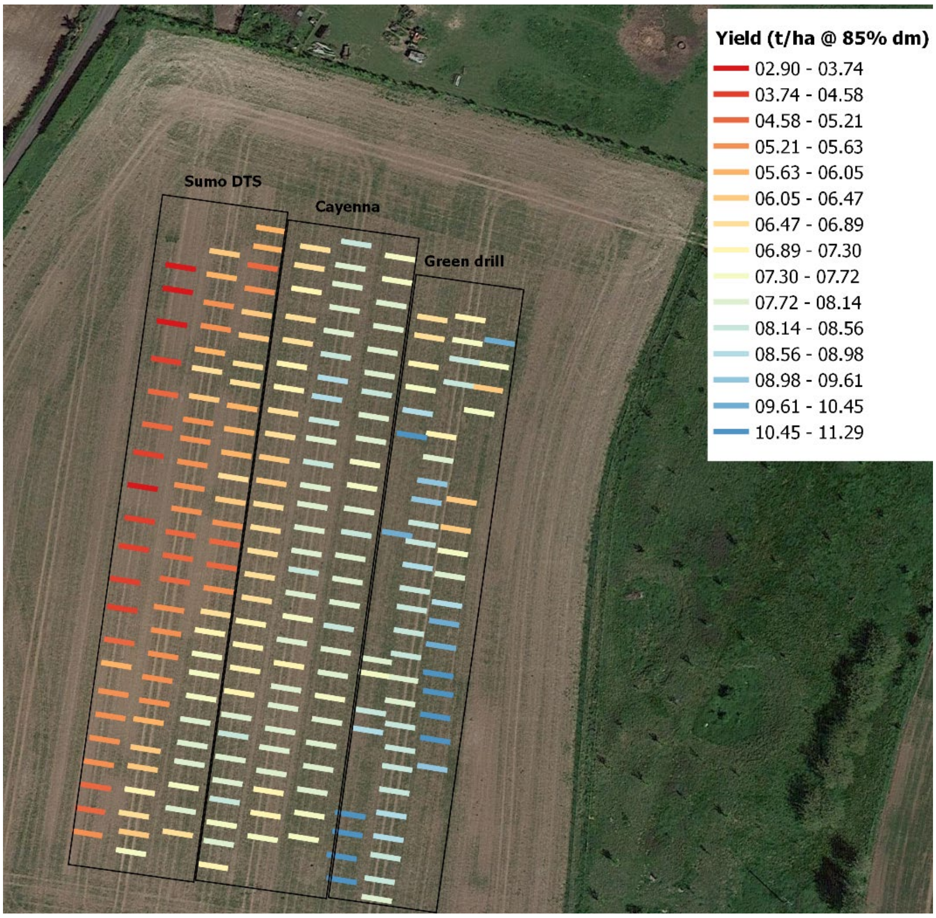


Figure 5-6 Spring barley yield map; Kent establishment trial (August 2018)

5.4.2. Winter oats (2019)

The field was disced and drilled with winter oats using a Sumo drill on 21/9/18 and harvested on 6/8/19. According to analysis of the yield map (Figure 5-7) using the Agronomics statistical model, there was no legacy effect of the different cover crop establishment treatments on the yield of winter oats (Table 5.6), with an average field yield of 9.2 t/ha.

Table 5.6 Winter oats yield (2019) as recorded using yield mapping with statistical analysis using Agronomics to predict the legacy effect of the cover crop treatments

Cover crop establishment method (2017)	Mean yield (t/ha @ 85% dm)	Difference in yield from the Sumo treatment t/ha (with 95% confidence limits)
1. Cayena direct drill		+ 0.18 (± 1.6)
2. GreenDrill cultivator		-0.33 (± 1.8)
3. Sumo DTS strip tillage	9.28	

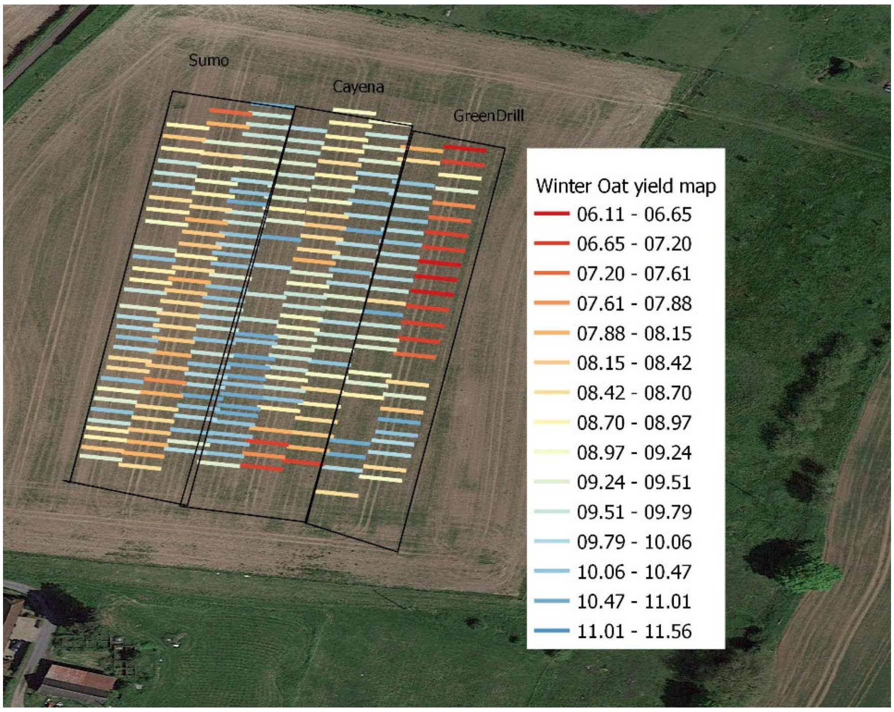


Figure 5-7 Winter oats yield map, Kent harvest 2019

5.4.3. Cost benefit analysis

Cumulative margin across the spring barley and winter oat crop at the Kent site are shown in Table 5.7. The lowest cumulative margin of £991/ha was measured on the Sumo DTS strip tillage drill (Farm Standard) treatment and the highest cumulative margin at £1554 was on the Amazone GreenDrill treatment, reflecting differences in yields of the following cash crops. The cost of the cover crop was £137/ha to £145/ha depending on the method of establishment.

Table 5.7 Cumulative margin for Kent (2018 and 2019)

Treatment	£/ha margin (2018)	£/ha margin (2019)	Cover crop cost £/ha	Cumulative margin £/ha
Amazone Cayena	834	668	*137*	1365
Amazone GreenDrill	1090	609	*145*	1554
Sumo DTS strip tillage	486	647	*142*	991
Margins based on spring barley at £175/t ; winter oats at £115/t; nitrogen at 55p/kg N (2018) and 59p/kg N (2019)				
Spring Barley Establishment costs £112/ha; seed costs £70/ha; fertiliser costs at £84/ha and spray costs at £135/ha and harvesting costs £100/ha *Winter Oats* Establishment costs £123/ha; seed costs £59/ha fertiliser costs at £83/ha and spray costs at £55/ha and harvesting costs £100/ha				

5.5. Overall evaluation - establishment trials

The success of the different methods of establishment was largely dictated by seasonal conditions (wet/dry autumns), with no one method fundamentally better for cover crop establishment. Establishment appeared to be ‘better’ following strip tillage at two of the sites, but this did not necessarily lead to increased cash crop yields and margins. Indeed, on the heavy textured soil in Yorkshire, although the cover crop mix drilled with the strip till farm drill gave rise to the greatest cover (as assessed by NDVI and confirmed by the host farmer), this led to a wetter topsoil where the cover crop biomass was greatest (due to the narrow window between cover crop destruction and spring crop (beans) establishment as a result of high rainfall; Dave Blacker, pers.comm); consequently spring bean establishment was poorer, with lower yields at harvest.

The establishment method should be considered in the light of the soil type, seasonal conditions and in the context of the resulting seedbed condition for sowing of the cash crop.

6. Farmer Experiences

6.1. Kent (Mark Bowsher Gibbs)

For several years, cover crops have formed part of the rotation for Blackbird farming at Hempstead Farm, near Sittingbourne, Kent. Here, about 70-100ha of cover crops are sown every year, comprising of feed oats, rye and vetch or Westerwold ryegrass. They provide an important food source for the farms flock of 1500 ewes, including 400 ewe lambs and are also included in the farms Ecological Focus Area (EFA) area.

The Maxi Cover Crop tramline trials conducted on the farm have provided a useful knowledge exchange platform with the Kent Monitor farm group. The group grow cover crops for a variety of different uses, with species mixes chosen depending on the soil/environmental issue that needs to be addressed. Results from the Maxi Cover Crop project has helped show the differences in performance between various mixes. The farmers have expressed doubt as to whether expensive mixes with a large number of species deliver more benefits than a simple cereal, and whether mixes containing vetch or clover are in the ground long enough to fix nitrogen.

Mark says “We now have some useful metrics to help quantify the benefits and ways of assessing the results. I’m a great believer in all-year-round cover, and holistically it has to be right. It’s only the practicalities and justifying the time investment that prevent us from making more use of cover crops.”

6.2. Yorkshire (Dave Blacker)

Dave uses cover crops ahead of spring beans on farm (the only spring crop grown on farm), only growing them if they can be drilled by the second week in September, otherwise they're not grown. The main reason for this is to allow sufficient time for cover crop growth.

One main change adopted in the last few years, is the timing of cover crop destruction (using glyphosate). Prior to the Maxi Cover Crop project cover crop destruction took place approximately three weeks before planting spring beans. However the results from the project demonstrated higher topsoil moisture content where cover crops had been grown compared with control treatments. The higher soil moisture content resulted in poorer establishment conditions for the following spring bean crop, which reduced yields compared to the control. As a result of these findings Dave now desiccates his cover crops, pre-Christmas, to give more time for seed bed preparation.

Dave hasn't seen a yield increase as a result of using cover crops, but has noticed a visual improvement in soil condition and structure.

6.3. Cambridgeshire Old Weston (Russ McKenzie)

Russ is now using catch crops (i.e. established and destroyed early ahead of winter cropping) as well as cover crops (i.e. kept in the ground over winter ahead of spring cropping) as these are a good management tool between winter crops to manage moisture levels in the soil and to avoid returning to cultivations. One example from 2018/19 when a spring oat cash crop was lost due to dry weather, Russ grew some additional buckwheat and phacelia as a catch crop to create a soil conditioning cover crop mix ahead of the 2019/2020 winter wheat crop.

Russ advises to not over complicate things. Ahead of spring crops, the species he tends to use include spring or winter oats, oil radish, phacelia and linseed. The use of cover crops and catch crops have reduced nitrogen fertiliser use on the farm. Russ is confident that the cover crops are capturing N and other nutrients, but he is uncertain as to when and how much is released back to the soil. Russ's estimate is that nitrogen is held for between two and three years before it is released. Russ is now experimenting with reducing fertiliser N inputs to account for N release from previous covers. One interesting example on farm, is that they had a contract for high N spring barley, which usually requires 145 kg N/ha, but as they had covers in the field a couple of years prior (oats, vetch, oil radish, phacelia, linseed) they decided to only apply 130 kg/N, and still met the contracted requirement. Russ felt this was due to the previous cover crop releasing the extra (15 kg/ha N) required.

Since converting to no-till and using covers they've seen soil improvements on farm, and can notice differences in soil quality and crop performance between those fields that have been in the new system for about 5 years and those that they haven't converted.

6.4. Cambridgeshire Benwick (commentary by Dick Neale, HLH)

The benefits of utilising cover crops are cyclical. The harvesting and storage of nutrients from the soil are now well documented and this is of huge benefit to the environment and where water contamination is an issue. However, for first time cover crop growers like at Benwick farm, it is believed that this removal of nutrients impacted yield in the cash crop compared to where no cover was grown. We also noted that where the cover has direct disc drilled (i.e. with the Weaving GD resulting in minimal soil movement) and the following cash crop was also direct disc drilled straight into the sprayed off cover, the negative yield impact was significant. Slug populations were noticeably worse in the direct drilled covers area and increased further where radishes formed part of the cover mix. A very large part of the yield reduction seen was negated when covers where lightly cultivated for establishment. We believe this allowed for better nutrient mineralisation from the soil, but undoubtedly it improved plant establishment through better seed soil contact at drilling and reduced slug grazing.

6.5. Overall experiences (commentary by Dick Neale, HLH)

From the grower perspective the learnings and success, frustrations or failures of cover cropping are largely based around seasonal conditions. There is no doubt that sowing as early as possible in August generates the best 'cover' from any species mix chosen. However, later sowings are inevitable because delayed harvesting conditions are not that unusual for the UK.

Cost and return was a strong feature of the study and while impacts on soil have also been measured, in a typical 3 year study the benefits to soil are likely to be overshadowed by the initial cost of the covers compared to any yield improvement or yield reduction seen in the following cash crops. Both positive and negative yield impacts have been seen in this study, some have been linked to the establishment system or drill used, and these have not proved straight forward to explain as to why, but there has been a clear linkage to yield reductions in spring barley where this followed cereal based covers, and this is supported in the data.

Black grass caused interference on several farms, particularly in year one of the Cambridgeshire establishment trials, which saw most covers not established until September. By January the covers were completely overrun by blackgrass and had to be sprayed off. This somewhat confused the effect of the covers, other than initial establishment in dry conditions was best from strip tillage systems rather than direct disc drill, again, we believe seed to soil contact in adequate moisture was the reason. At the Benwick farm there was no yield impact from the covers that year in spring barley but at Old Weston a negative yield impact was observed in spring beans. This was minimal where the beans where strip till drilled but significant where minimal soil disturbance at drilling was practised. The yield loss was again due to poor initial establishment of plant numbers. It has been observed at several points in the study that a degree of soil movement, either during establishment of the cover crop or prior to sowing the cash crop, has resulted in higher cash crop yield. These were observations within the study, and are not supported by the measured data and appear to be related strongly to drill type used (very low disturbance disc).

The needs of various soils across the UK is most likely not met consistently by a fixed species mix as predominantly utilised within studies of this type. In northern England one of the dominant features of a cover crop should be the ability to 'pump water' out of the soil at a significant rate, while in southern and eastern counties this would be less desirable. Light and silty soils require species to aggregate and stabilise the soil but in all cases the species mix utilised must take into account the following crop so that any antagonism is avoided.

The Maxi-Cover crop study goes someway to highlight the impact of individual cover crop species regarding impact on the soil and direct yield impacts on a crop of spring barley. However, at the farm level, extending from Kent to Cambridgeshire and Yorkshire, seasonal issues had a greater impact than any specific cover crop mix, drilling date, destruction or following crop. Dry autumns impacted cover establishment in the south and wet springs impacted the sowing of spring crops in the north.

7. Discussion

In a survey of UK farmers, the three most cited reasons for not growing cover crops were, (i) they did not fit with the current rotation, (ii) expense and (iii) the difficulty of measuring their benefit (Storr et al. 2019). The Maxi Cover Crop project aimed to address some of these issues by characterising the performance of a range of cover crop species both individually and in mixes of increasing complexity under field conditions, and by performing a cost benefit analysis on the systems used. The project has measured, assessed and quantified where possible the benefits of the cover crops to soil properties and the performance of the subsequent two crops in the rotation, and provided new data on how cover crops root. It has also provided a template for growers to perform a cost/benefit analysis of using cover crops in their own rotations. A key feature of the work has been the use of tramline trials on commercial farms to complement the work undertaken on the more traditional field experimental plots, thereby extending the database to cover a wider range of soil types (particularly heavy textured soils which were absent from replicated plot experiments), using field scale comparisons of treatments in a commercial setting. However, it is important to note that the Maxi Cover Crop Project quantified the effect of cover crops grown once in the rotation and effects followed through the following spring and winter crops. The benefits and effects of cover crops are likely to increase over long term and best studied over multiple applications and seasons, although long term studies of cover crops are uncommon, with most lasting 2-3 years (Abdalla et al. 2019).

7.1. Species selection and management

The results confirm that early establishment (by the end of August) is essential, regardless of the cover crop species grown, in order to maximise benefits (in terms of crop cover, biomass production, nutrient uptake and rooting by the cover crop). Table 7.1 summarises the key characteristics of the different cover crop species observed in the Maxi Cover Crop study. Radish and buckwheat were quick to establish, in terms of above ground green cover, but below-ground, it was rye that produced the greatest root length (and diameter) early in the season, which was maintained until destruction. Phacelia was also good at producing both above and below ground biomass and although roots were slower to develop compared to the rye, by destruction it had the highest SRL in the topsoil. Phacelia produced a high density of fine roots suggesting it explored more of the soil for a given root biomass compared to the other cover crop treatments. Buckwheat also established early, but did not root well and was destroyed by the first frost. Similar differences in rooting between phacelia (high RLD) and buckwheat (low RLD) have been reported in the literature, with buckwheat reported to have a low dry matter allocation to the root system (Bodner et al. 2014; Yu et al. 2016; section 2.2.2).

In terms of rooting traits, a high root density and thickness have been suggested to be important features for improving soil structure, and a species with a high SRL is considered to be most effective (Yu et al. 2016). In this study, both rye (high RLD to depth and wide root diameter) and phacelia (high RLD, particularly in the topsoil, narrow roots and high SRL) showed these characteristics that were linked to improved soil structure. These findings contrast with the work by Yu et al (2016), who suggested legume species were most beneficial at improving soil structure. However, differences in rooting between the cover crop species in the replicated plot trials did not lead to any measurable differences in soil properties, and there was no evidence of 'bio-drilling' i.e. where the roots of one crop create pores and pathways for the roots of the subsequent crop (Cresswell and Kirkegaard, 1995), with no relationship observed between cover crop RLD and spring crop RLD. This may be a reflection of the soil types and cultivation history of the replicated plot experimental sites (cultivated, light and medium textured soils), with the beneficial effect of biopores more evident in compacted soils and at lower tillage intensities (Landl et al. 2019). There was, however, some evidence of improved soil structure (lower penetration resistance, bulk density and VESS scores) following use of the cover crop mixtures at the two of the tramline trial sites on medium textured soils, with one of these sites also reporting higher earthworm numbers following mix 3 (containing 5 species; this mix wasn't grown at the other medium-textured tramline trial site). There was no effect of the cover crop mixes on soil properties at the two heavier textured tramline trial sites.

Table 7.1 Key characteristics of the cover crop species measured by the maxi-cover crop project

Cover crop	**Key characteristics measured in maxi-cover crop**
Oil radish (Terranova)	Rapid establishment, good early cover, high N uptake
Buckwheat (Lileja)	Rapid establishment but destroyed by first frost; low root production; some evidence of an increase in P supply to the following crop
Phacelia (Natra)	Roots slower to develop, but good N uptake and rooting by destruction; high density of fine roots in the topsoil
Cereals: spring oats (Canyon) and rye (Inspector)	High root length density to depth and high N uptake if established early; negative effect on yield of subsequent spring cereal crop if grown as a straight
Legumes: vetch (Amelia) and crimson clover (Contea)	High N recovery (N fixation), particularly if established early.

For N uptake, the results suggest that ability to fix N (i.e. clover and vetch), rapid above and below ground establishment (radish, rye) plus good root exploration (phacelia) were important in determining overall N recovery, with up to 90 kg/ha N recovery possible over the winter period (typically 30-50kg/ha). Soil type and moisture were also important factors, with the highest N recovery measured on the heavier textured site. This level of N uptake is similar to previously reported for cover crops in the UK (see section 2.2.1), but differences in N uptake by the cover crops (< 25 kg/ha to 90 kg/ha) had no impact on the N recovery of the subsequent two cash crops in the rotation. The cash crops received recommended rates of N fertiliser addition, as a flat rate across all treatments (no adjustment due to cover crop N recovery) which may have 'masked' subtle differences in cover crop N release and recovery by the cash crops. The fate of N taken up by cover crops remains a key research question, with impacts not only on the fertiliser policy of subsequent crops in the rotation, but also N loss to the wider environment.

There was clear evidence of a negative impact of growing cereal cover crops (oats and particularly rye) on the performance of the subsequent spring barley cash crop, in terms of rate of crop establishment, rooting to depth and ultimately grain yield. The reason for this is uncertain, but N immobilisation, pest and pathogen carry-over ('green bridge') and allelopathy have all been cited as possible causes. N immobilisation following a rye cover crop has been reported in a number of studies (Crandall et al. 2005; Krugger et al. Nevin et al. 2020), with the effects on the following crop dependent on the timing of destruction and subsequent N fertiliser policy. For example, Crandall et al. (2005) only measured reductions in corn yield where the rye cover crop was destroyed late (within 1 week of drilling) and N fertiliser was applied as a single dressing late in the season. However, allelopathy may also explain the lower yields, for example, Li et al. (2013) attributed lower cotton growth and yield on a clay loam soil in Texas following a rye or wheat cover crop (compared to no cover) to higher concentrations of three allelochemicals measured in the soil at cover crop destruction. Whereas, Bakker et al. (2016) showed that the roots of rye cover crops host a number of pathogens capable of causing corn seedling disease.

It is uncertain whether the detrimental effect of a cereal cover crop can be negated by including it in a mixture. For oats, this appeared to be the case in the replicated plot experiments, where yields following mix 1 (83% oats) and mix 3 (55% oats) did not decline, although spring barley rooting was highest following mix 2 which had no cereal content ($P<0.05$ compared to rooting following the straight oat cover crop only). Likewise at the tramline trial sites, spring barley yields were not affected at two of the three sites growing mixes containing cereals. However, at one site yields were lower where cover crops had been grown, but this was the case for both mix 1 (83% oats) and mix 2 (no cereal content). The yield decreases at this site were most likely to be due to the method of crop establishment (low disturbance disc drill with no prior cultivation) and slug damage (Dick Neale, pers.comm). Rye was not included in any of the mixes tested, so it is uncertain whether inclusion of rye in a mix would be beneficial. These results have implications for the CAP EFA greening rules, which require cover crop mixes to include a cereal and non-cereal. However, although the results suggest cereal cover crops should be part of a mix rather than grown as a straight, there was no clear evidence that the performance of the other cover crop species (notably radish and phacelia) was improved by inclusion within a mix. Hallama et al. (2018) suggested that cover crop mixes were superior to monocultures in terms of biomass production, nutrient uptake and impact on cash crop performance, but based this conclusion on a limited number of studies largely focusing on maize production. At the Maxi Cover Crop sites, nitrogen uptake was greatest when radish and phacelia were mixed with a legume (i.e. in mix 3; $P<0.05$ compared to the straight phacelia and radish treatments), but this was not significantly different to the total N uptake by the straight clover treatment, with no difference in spring barley grain yields following the cover crop mixes, straight radish, phacelia or clover treatments. Crotty and Stoate (2019) demonstrated that complex cover crop mixes resulted in greater soil biodiversity compared to simple ones and monocultures. Soil biodiversity was not measured within the Maxi Cover Crop experiments, although there was some evidence of improved biological functioning (earthworm numbers and diversity) following the 5 species mix (mix 3) compared to the two species mix (mix 1) at one of the tramline trial sites. However, this was not seen at the three large plot experimental sites where mixes were compared with monocultures.

Cover cropping also reduced spring bean yields at one of the tramline trial sites. This was not, however thought to be due to the species present in the cover crop mix, but a consequence of soil type and timing of destruction. It is clear from both the replicated plot trials and tramline trials that cover cropping on heavy textured soils, particularly clays, can result in increased topsoil moisture, probably due to the presence of the cover crop preventing surface evaporation. In these circumstances, late destruction (< 1 week prior to drilling) and a high cover crop biomass (as found in the establishment tramline trials where the covers were strip till drilled) can result in a poor seedbed for subsequent cash crop establishment, with wet soils also more susceptible to compaction.

A key finding of the research, which requires further confirmation and evaluation is the trend for a higher spring barley grain P concentrations where buckwheat had been grown. This only appeared to be the case where buckwheat had been grown as a straight, not as part of mix 2 (50% of the mix) or 3 (19% of the mix). The mechanism for this enhanced P uptake is unclear, as above ground biomass and rooting by the buckwheat were low compared to the other cover crop treatments, and the crop was destroyed by the first frosts (November) at all sites. As discussed in section 2.2.1, this may be due to P solubilisation by root exudates, but further work is required to understand the processes involved, and given the cost of buckwheat seed (£128/ha; Table 3.5) to also determine the proportion of buckwheat required in a mix to achieve this benefit (the absence of any effect following mix 2 and 3, suggests that it needs to be greater than 50% of the mix).

7.2. Farm economics

The cumulative (2 year) margins for the key cover crop species and mixes are summarised according to soil type in Table 7.2 to Table 7.4. Across the seven experimental sites, there were twenty comparisons of cumulative (2 year) margins ± cover crop. Most (95%) showed a reduction in margin compared to no cover crops, with margins ranging from + £64/ha following oil radish on a clay loam, to - £476/ha following a two species mix on a clay soil (average: - £150/ha). The reductions in cumulative margin were due to lower cash crop yields following cover crops or the absence of a sufficient yield benefit to compensate for the additional seed and establishment costs. There was also no clear trend to demonstrate that cover crops were more economical on certain soil types, however, there was a suggestion that where the impact of a cover crop resulted in a significant yield reduction, greater losses in cumulative margins occurred on the heavier soil types (see Table 7.3), with reductions in the region of £350/ha. Higher margins mostly occurred where yields were increased.

Table 7.2: Cumulative margin for replicated plot experiments according to soil type. Margin response (Increase ⇑ or decrease ⇓, according to Control)

	Soil type	
Treatment	Sandy Loam	Clay Loam
No cover	1033	1192
Oil Radish	944 ⇓	1256 ⇑
Spring Oats	884 ⇓	879 ⇓
Phacelia	940 ⇓	1110 ⇓
Mix 1	944 ⇓	1055 ⇓
Mix 2	859 ⇓	1177 ⇓
Mix 3	988 ⇓	1029 ⇓

Table 7.3: Cumulative margin for cover crop validation trials according to soil type. Margin response (Increase ⇑ or decrease ⇓, according to Control)

	Cumulative margin (£/ha)			
Treatment	Loam	Silty Clay Loam	Clay/clay loam	Clay
Control (Stubble)	1301	825	1177	943
Mix 1	1249 ⇓	521 ⇓	1105 ⇓	467 ⇓
Mix 2	-	446 ⇓	-	662 ⇓
Mix 3	1275 ⇓	-	1052 ⇓	-

Table 7.4: Cumulative margin for cultivation validation trials according to soil type. Margin response (Increase ⇑ or decrease ⇓, according to Control, farm standard cultivation shown in italics)

	Cumulative margin (£/ha)	
Treatment	Loam	Clay
1. Cayena direct drill	1365 ⇑	746 ⇑
2. GreenDrill cultivator	1554 ⇑	705 ⇑
3. Sumo DTS strip tillage	*991*	-
4. Mzuri strip till drill	-	*644*

Benefits from changes in soil physical properties or nutrient dynamics are slow to manifest themselves and the longer-term use of cover crops over a full rotation (including more than one year of cover cropping) should be used to fully assess the impact on margins. This has been evaluated on the NIAB led New Farming Systems (NFS) project (see section 2.2.3). Over the rotation (8 seasons) cover crops had little impact on margins (with three iterations of cover crops sown). On average (across the different tillage systems tested) a cumulative margin of £5,194/ha (including the cost of cover crop seed and establishment) was recorded from the use of brassica cover crops, compared to £5,254/ha without the inclusion of cover crops (Nathan Morris, pers. comm). There was also some indication that shallow tillage (for all crops in the rotation) led to a slight increase in margin where cover crops were grown compared to shallow tillage without cover crops, although this was not significant.

Cover cropping is often associated with reduced tillage systems (Storr et al. 2019) and studies have shown that lower operational costs (fuel and labour) of non-inversion tillage systems can potentially increase farm margins by £10-£85/ha compared to conventional ploughing (Deasy et al. 2009; Morris et al. 2010). Savings in fuel and labour costs could potentially offset the cost of the cover crop seed (£30 - £130/ha, depending on the species and mix; Table 3.5). Other costs associated with cover crop use (e.g. drilling if not conducted as part of the cultivation pass, slug control etc) are likely to require an increase in the yield of the following cash crop to offset the overall cost of using cover crops when assessed over a single year. Work carried out by Cooper et al. (2017), showed at the catchment scale that higher operational costs associated with the establishment of cover crop and non-inversion tillage regimes were offset by increased yields in the subsequent cash crop, resulting in comparable gross margin (£731–758/ha) to conventional ploughing with fallow (£745/ha). There may be some scope for additional cost savings by reducing nitrogen fertiliser to account for the N captured and released by the cover crop. The Nutrient Management Guide – RB209 (AHDB 2020) suggests that 'early destruction of a well-established cover crop by the end of February can release useful quantities of nitrogen for the following spring crop – sufficient to increase the SNS by up to 2 indices'. This could be worth between £6 and £30/ha (assuming an N fertiliser price of £0.59 /kg N and average N uptake values measured at the Maxi Cover Crop replicated plot experiments of 10-50 kg N/ha), although as discussed above there is uncertainty regarding when this N will become available.

It is important to consider the wider benefits cover crops provide, such as improved water quality or erosion control. These benefits are an important consideration for mitigating against environmental pollution and providing ecosystem services to the wider public. The CAP Greening Measures payment aims to reward farmers for some of these benefits, although the payments are considered to be rather restrictive. In the UK survey of farmers conducted by Storr et al. (2019), 71% of farmers growing cover crops, reported that the EFA guidelines for cover and catch crops were not suitable. Use of cover crops in 'Payment for Ecosystem Services' (PES) schemes have been explored by a number of water companies in the UK and it is envisaged that cover crops will be a part of future Environmental Land Management schemes (ELMs). At the European level, it has been suggested that EFAs will not be retained in the CAP after 2020, but will be incorporated into required standards for good agricultural and environmental condition of land, known as "GAEC" conditions (Commission 2018b; Shackelford et al. 2019). In GAEC 7 there is a requirement for "no bare soil in most sensitive period(s)"; consequently the use of cover crops is likely to play an important role in achieving this (Commission 2018a; Shackelford et al. 2019).

The wider use of cover crops may also facilitate grazing by livestock if suitable species are chosen for their palatable and nutritional value. This can also provide an additional income to growers although this income will be dependent on the duration of grazing and the type of livestock enterprise considered. It is likely that investment in additional infrastructure such as fencing and water supplies will be required to support livestock production in areas currently in predominantly arable production.

7.3. Future research

Maxi Cover Crop has advanced our knowledge of the physiology and performance of a range of cover crop species, particularly in relation to the way they root, take up nitrogen and affect the performance of the subsequent cash crops. It has also provided useful insights into the practicality of using cover crops across a range of soil and climatic conditions and provided data on the cost and benefits of including cover crops in rotations. The work has highlighted a number of gaps in our knowledge; specifically further work is required on:

- Understanding the fate of N recovered by cover crops – when this N is released and how much is released. The ability to predict mineralisation rates for different cover crop species grown on contrasting soil types in different agro climatic zones will improve fertiliser recommendations for subsequent cash crops.
- Evaluating alternative methods for destroying cover crops rather than relying on glyphosate (e.g. grazing, chopping, crimping, rolling). Understanding the limitations of techniques for managing contrasting cover crops is important to improve guidance for cover crop management and the implications for subsequent cash crop establishment and effects on soil properties and N supply.
- Evaluating the long-term (multiple cycles of cover cropping) benefits of cover crops. What are the benefits for soil organic matter, soil biology and associated soil properties.
- Quantifying the economics of growing cover crops and the potential income from livestock grazing or the reduction in inorganic nitrogen fertiliser application in the following cash crop.
- This study showed that rye and to lesser extent spring oats resulted in slower development of spring barley early in the season and lower yields at harvest. Further work is required to understand the cause of the cash crop yield reductions (e.g. nutrient availability, disease pressure, etc) and whether cover crop mixes can be developed that do not lead to reduced yields. This has implications for EFAs which require cover crop mixes to include a cereal and non-cereal.
- In this study, there was some evidence suggesting that buckwheat may enhance P availability to the following cash crop. However, further work is needed to understand the mechanism for this, and given the cost of buckwheat, how much of a cover crop mix needs to be buckwheat for this benefit to be achieved.

8. Knowledge Exchange

Maxi Cover Crop has featured at a wide variety of knowledge exchange events, press articles and scientific conferences:

Events:

- ADAS Gleadthorpe Open Event, 26th April 2017
- ADAS High Mowthorpe Farmers Association 16th Jan. 2019
- ADAS Gleadthorpe Farmers Association 27th Feb. 2019
- ADAS/AHDB Rosemaund open day (June 2018)
- AHDB/ADAS/BBRO cover crops for soil improvement: Stetchworth (Jan. 2019)
- AHDB Agronomy South East & Agronomy South West (14 & 15th Jan. 2020)
- AHDB Strategic Farm East open day; 6th June 2019
- Crop Tec Show (November 2017)
- Groundswell 26th and 27th June 2019
- Huggate Monitor Farm meeting (November 2018)
- Hutchinsons Farmer meeting & company conference 2017
- Hutchinsons open days/farmer meetings: June 2017 & 2018; Dec. 2019 & Jan. 2019
- NIAB Morley open day 22nd June 2017; Member Results day (Jan 2017)
- RAGT open days: 24th & 25th May, 20th & 21st June, 5th July 2017; May 2018
- Sittingbourne Monitor Farm meeting (Dec. 2018)
- Suffolk & Essex water & pesticides meeting (Nov. 2018)
- Warrington Monitor Farm meeting (March 2018)

Press articles:

- Arable Farming Research in Action, July 2018: '*Autumn drives cover crop value'*
- CPM Magazine Highlight, April 2017: '*Uncovering the science to cover cropping'*
- CPM article June 2019: '*A clearer course for cover crops'*
- NIAB Landmark Article, May 2017: '*Cover crops: benefits, management practices and knowledge gaps'*

Conference presentations, papers or posters:

- AAB Meeting: Soil Improvement: Impact of Management Practices on Soil Function and Quality. Aspects of Applied Biology 140. Oct. 2018
- International Fertiliser Society: Maximising the benefits from cover crops. 13th December 2019.

9. Acknowledgements

The authors wish to thank RAGT seeds (Helen Wilson) for the provision of all the cover crop seed for the experimental sites and chemical analysis of the grain (N and P) and cover crop (P) contents; Hutchinsons (Dick Neale) for co-ordination of the establishment tramline trials; Amazone for participating in the establishment tramline trials; and our host farmers: Stetchworth Estates, Leyfields Ltd (Kneesall), EM Wilkison & Sons (Wilberfoss), David Blacker, Mark Bowsher Gibbs, Russel McKenzie and Gary Thacker.

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11. Appendices

11.1. Appendix A – Cost/benefit (margin) template

	Crop: Description:	Crop: description:	Crop: Description:
Yield (t/ha) **Grain price (£/t)** **OUTPUT (£/ha)**	**0.00**	**0.00**	**0.00**
MINUS VARIABLE COSTS: Cover crop seed Cover crop sprays Crop Seed Fertiliser Sprays **VARIABLE COSTS (£/ha)**	**0.00**	**0.00**	**0.00**
GROSS MARGIN - (£/ha)	**0.00**	**0.00**	**0.00**
MINUS FIELD OPERATIONAL COSTS (£/ha) Subsoil Direct Drill (tine) Roll Slug pelleting (x) Fertiliser (x) Sprayer (x) Combining **TOTAL FIELD OPERATIONAL COSTS (£/ha)**	**0.00**	**0.00**	**0.00**
PLUS OTHER UNQUANTIFIABLE BENEFITS (£/ha) E.g. Reduction in nitrate loss			
MARGIN MINUS COSTS PLUS OTHER BENEFTS (£/Ha)	**0.00**	**0.00**	**0.00**

11.2. Appendix B – Cover crop root traits

11.2.1. Early rooting (c. 2 months growth)

Cover crop root length (cm), dry weight (g), average diameter (mm) and specific root length (m/g) (cm) after c. two months growth, across all three experimental sites (cross site averages). Results are an average of 10 plants per plot (12 for mix 2), and exclude roots > 3mm in diameter which could not be scanned (except for the dry weight and SRL calculations which include manual measurements of the radish taproot), with results expressed on a per plant basis. 5 plants/species, 4 plants/species and 2 plants/species were sampled from mix 1, 2 and 3, respectively. Sampling was undertaken prior to destruction of the buckwheat by frost. Control treatment includes volunteer cereals and weeds.

Treatment	Length (cm/plant)	Dry root wt (g/plant)	Diameter (mm/plant)	Specific root length (m/g)
Control	151.7	0.029	0.35	56.78
Radish	257.7	0.351	0.34	20.22
Oats	189.8	0.033	0.37	62.52
Rye	395.1	0.038	0.27	97.98
Vetch	146.5	0.032	0.49	48.24
Clover	220.8	0.027	0.30	78.72
Buckwheat	99.15	0.029	0.29	52.76
Phacelia	117.5	0.042	0.35	44.83
Mix 1	179.0	0.025	0.35	74.37
Mix 2	162.3	0.097	0.30	42.44
Mix 3	151.3	0.079	0.33	55.29
Mean	*187.8*	*0.07*	*0.34*	*57.54*
REML F	<0.001	<0.001	<0.001	<0.001
SED	17.98	0.005	0.0114	5.295
LSD	35.33	0.01	0.02	10.40

11.2.2. Rooting at cover crop destruction

Cover crop root length density (RLD, cm/cm^3), dry weight (mg/cm^3), average diameter (mm) and specific root length (SRL, m/g) of the straights and mixes at cover crop destruction. Cross site averages. N.B. this doesn't include the radish taproot due to the nature of sampling. *Buckwheat had been destroyed by frost *c.* 1-2 months prior to this sampling – rooting on this treatment therefore largely represented volunteer cereal and weeds, which is also the case for the control treatment.

Treatment	RLD (cm/cm^3)				Root DW (mg/cm^3)				Average Diameter (mm)				SRL (m/g)			
Soil depth (cm)	0-20	20-40	40-60	Mean	0-20	20-40	40-60	Mean	0-20	20-40	40-60	Mean	0-20	20-40	40-60	Mean
Control	2.47	0.78	0.44	1.23	0.10	0.05	0.04	0.06	0.19	0.19	0.18	0.19	259	183	147	196
Radish	5.43	1.36	0.51	2.43	0.19	0.08	0.05	0.10	0.18	0.22	0.23	0.21	360	238	168	255
Oats	4.58	0.91	0.65	2.10	0.21	0.07	0.05	0.11	0.21	0.24	0.20	0.22	275	172	148	200
Rye	8.11	1.40	0.64	3.38	0.31	0.09	0.05	0.15	0.19	0.24	0.26	0.23	295	194	165	218
Vetch	4.02	0.60	0.45	1.69	0.17	0.05	0.04	0.09	0.22	0.24	0.19	0.22	286	155	124	188
Clover	4.60	0.72	0.52	1.95	0.16	0.05	0.03	0.08	0.20	0.23	0.20	0.21	298	193	146	212
'Buckwheat'*	2.53	0.55	0.36	1.15	0.12	0.04	0.03	0.06	0.19	0.19	0.18	0.19	269	203	127	199
Phacelia	8.72	1.11	0.60	3.47	0.32	0.06	0.04	0.14	0.17	0.20	0.19	0.19	393	224	186	268
Mix 1	5.91	0.87	0.57	2.45	0.23	0.07	0.04	0.12	0.22	0.25	0.21	0.23	274	206	137	206
Mix 2	7.19	1.08	0.58	2.95	0.26	0.07	0.05	0.12	0.17	0.20	0.20	0.19	376	230	156	254
Mix 3	6.15	1.47	0.71	2.77	0.23	0.08	0.04	0.12	0.19	0.22	0.21	0.20	351	219	187	252
Mean	5.43	0.99	0.55	2.33	0.21	0.06	0.04	0.10	0.19	0.22	0.20	0.21	312	201	154	223
REML:	Treat	Depth	Treat*Depth		Treat	Depth	Treat*Depth		Treat	Depth	Treat*Depth		Treat	Depth	Treat*Depth	
F	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001		<0.001	<0.001	0.223		0.005	<0.001	0.95	
SED	0.41	0.21	0.70		0.009	0.005	0.015		0.006	0.003	0.011		21.09	11.01	36.52	
LSD	0.80	0.42	1.39		0.017	0.009	0.030		0.012	0.006	0.021		41.58	21.71	71.8	

11.3. Appendix B – Cost benefit analyses (Large plot experiments)

11.3.1. Stetchworth – Cumulative margin (2017-2018)

Treatment	£/ha margin (2017)	£/ha margin (2018)	Cover crop cost £/ha	Cumulative margin £/ha
No cover	191	842	*0*	1033
Oil Radish	132	880	*68*	944
Spring Oats	91	859	*66*	884
Rye	109	860	*74*	895
Vetch	106	888	*127*	867
Crimson clover	152	821	*84*	889
Buckwheat	153	879	*167*	865
Phacelia	139	890	*89*	940
Mix 1	132	908	*96*	944
Mix 2	71	894	*106*	859
Mix 3	149	958	*119*	988

Margins based on spring barley at £135/t ; winter barley at £155/t; nitrogen at 64p/kg N (2017) and 55p/kg N (2018)

<u>Spring Barley</u>
Establishment costs £148/ha; seed costs £77/ha; fertiliser costs at £77/ha and spray costs at £115/ha and harvesting costs £100/ha
<u>Winter Barley</u>
Establishment costs £208/ha; fertiliser costs at £96/ha and spray costs at £169/ha and harvesting costs £100/ha

11.3.2. Kneesall – Cumulative margin (2018-2019)

Treatment	£/ha margin (2018)	£/ha margin (2019)	Cover crop cost £/ha	Cumulative margin £/ha
No cover	715	478	*0*	1192
Oil Radish	845	478	*67*	1256
Spring Oats	463	481	*65*	879
Rye	584	429	*73*	940
Vetch	894	484	*127*	1252
Crimson clover	719	439	*83*	1074
Buckwheat	775	484	*167*	1093
Phacelia	746	452	*88*	1110
Mix 1	698	452	*95*	1055
Mix 2	785	497	*105*	1177
Mix 3	653	494	*118*	1029

Margins based on spring barley at £175/t; winter oilseed rape at £325/t; nitrogen at 55p/kg N (2018) and 59p/kg N (2019)

<u>Spring Barley</u>
Establishment costs at £148/ha; seed costs at £80/ha; fertiliser costs at £77/ha; spray costs at £112/ha and harvesting costs at £100/ha
<u>Winter Oilseed Rape</u>
Establishment costs £230/ha; seed costs £60/ha; fertiliser costs at £100/ha and spray costs at £138/ha and harvesting costs £100/ha

11.3.3. Wilberfoss – Cumulative margin (2018-2019)

Treatment	£/ha margin (2018)	£/ha margin (2019)	Cover crop cost £/ha	Cumulative margin £/ha
No cover	192	-	*0*	192
Oil Radish	303	-	*111*	193
Spring Oats	357	-	*109*	248
Rye	155	-	*117*	38
Vetch	105	-	*170*	-65
Crimson clover	383	-	*127*	256
Buckwheat	288	-	*210*	78
Phacelia	314	-	*132*	182
Mix 1	328	-	*138*	189
Mix 2	349	-	*149*	200
Mix 3	286	-	*162*	124
Margins based on spring barley at £175/t; nitrogen at 55p/kg N (2018)				
Spring Barley *Establishment costs at £138/ha; seed costs at £61/ha; fertiliser costs at £77/ha; spray costs at £82/ha and harvesting costs at £100/ha* *Following crop* *Due to the following crop being sugar beet margins were not possible to be calculated over the two seasons*				