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'Added value fallows'

The use of customised cover cropping approaches within integrated grass weed management

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CONTENTS

1. Abstract

Concerns about soil health and sustainability have led to an increasing interest in and adoption of cover cropping approaches to both improve soil health and crop rotation performance. Alongside rotational diversity and the adoption of no-till or reduced cultivation, cover crops form the basis of conservation agriculture. At the same time, across the industry, there is increasing pressure from grass weed species, such as black-grass, Italian rye-grass, bromes and wild oats. This is as a result of the development of herbicide resistance (in some species) combined with a reduction in available herbicide active ingredients. The increased adoption of systems with lower cultivation intensity, allied to increasing use of cover crops, could potentially exacerbate grass weed problems. Such systems can reduce the out-of-cropping opportunities for grass weed control (eg stale seedbeds and/or use of glyphosate for total weed control) and limit use of inversion to bury fresh weed seeds. This project aimed to address this conflict to evaluate the risk/reward balance, specifically with regard to the use of cover cropping where black-grass pressures are high.

Although cover crops have value in the rotation, the research trials and modelling carried out as part of the project confirm that, in relation to the management of black-grass in arable rotations, cover crops should be seen as having a neutral or slightly negative effect on weed population dynamics. The potential negative effects can, nonetheless, be mitigated by careful management. It is clear that other agronomic factors have much more significant effects on the population dynamics of grass weeds, such as black-grass, including: cultivation timing and type, use and timing of glyphosate outside of the crop, the date of crop establishment and the diversity of rotation. Many of these agronomic variables are modified when cover crops are introduced and their effects can be confused or confounded with the direct effects of cover crops. This project has found that the direct effects of cover crops on black-grass are small – almost all the effect on populations in field trials could be explained by the underlying cultural control approach. Therefore, maximising the effectiveness of a cover crop strategy as part of a black-grass control strategy involves maximising the effectiveness of the underlying cultural control approach.

This project, therefore, concludes that cover cropping should continue to be considered as a support to the sustainable production of crops. However, the role of cover crops in modifying the population dynamics of black-grass should not be overstated.

2. Introduction

Rotations of predominantly winter crops are under threat in much of the arable cropping area of the UK from herbicide resistant black-grass. Consequently farmers are seeking to integrate cultural approaches into their weed management strategies. Spring cropping is probably the most powerful cultural ‘weapon’, however, there is a need to maximise its effectiveness against grass weeds and develop management guidance to help crop production. At the same time, concerns about soil health and sustainability have led to an increasing interest and adoption of cover cropping approaches to both improve soil health and, in specific situations, crop performance.
In this context, cover crops have been suggested as a tool to further enhance weed management. Three main mechanisms may contribute to this effect:

1) weeds are smothered by the cover crop;
2) mowing effectively controls annual weeds promoting further suppression by the perennial cover crop, and;
3) germination of weeds in the following crop may be inhibited by incorporating the cover crop residue (so called ‘biofumigation’).

Species vary in their relative efficacy in terms of optimising these different components of weed suppression (e.g. Figure 1). For example, by producing a dense canopy, rye cover crops compete effectively with weeds for light, moisture, and nutrients, resulting in a suppression of their growth. However, the effects of cover crops are complex and varied e.g. Brennan & Smith (2005) found that a legume and oats mix, allowed burning nettle to produce large amounts of seed due to poor early season growth, and that this increased weed management costs in subsequent crops in a tilled vegetable system on the central coast of California. This study evaluated three cover crops and of these mustard was reported to be the best for weed control given its early season growth and weed suppressive abilities (Brennan & Smith 2005).

Existing literature on the potential for the plant residues of brassica species to suppress seed growth and/or establishment has indicated some benefits but results are mixed (e.g. Norsworthy et al. 2004). To date there has been no direct consideration of the key grass weed species that are a priority for UK cereal production. The mechanism for these allelopathic or biofumigant properties is well established; glucosinolates occurring in brassica species are hydrolised into isothiocyanate compounds in the soil (Morra & Kirkegaard, 2002; Gimsinga & Kirkegaard, 2006). However, multiple variables affect the degree of control achieved. Levels of glucosinolates vary between brassica species and varieties, the conversion of glucosinalates to isothiocyanates is variable and dependent on the techniques adopted for incorporation of plant residues. But despite a lack of quantitative data, a range specialist of ‘biofumigant’ brassica species and varieties are being promoted for use as a component of integrated weed management in the UK.

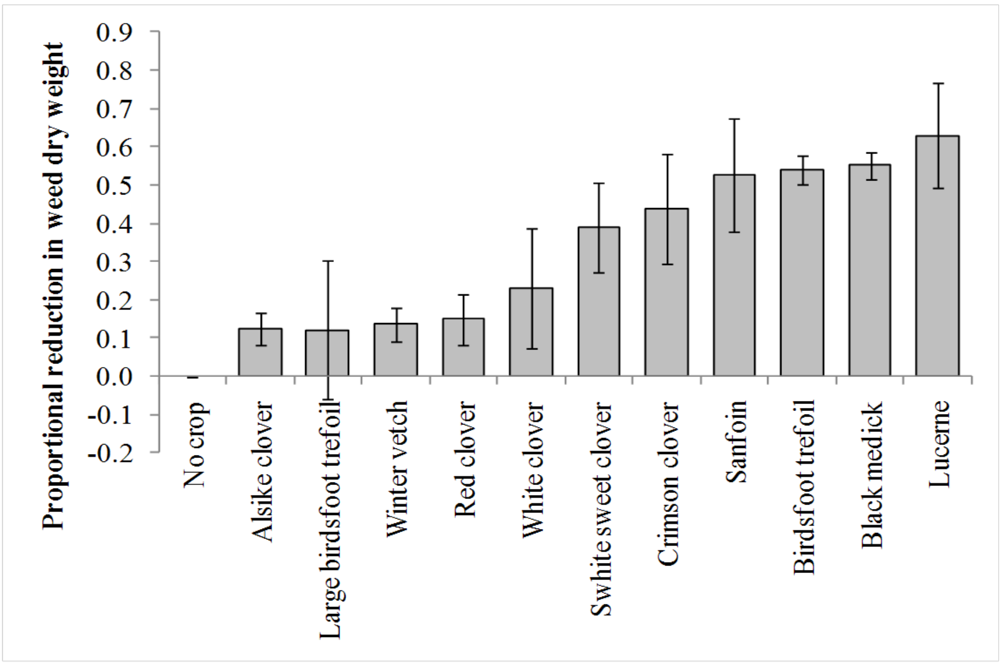

Figure 1. Reduction in biomass of fat hen plants (mean of observations of 5 plants in each plot, with the standard error of the mean shown as an error bar) in plots of different legume cover crops compared with the weed growing in bare fallow (no crop). The full experiment is described in Storkey et al. (2011).

The potential value of cover cropping approaches within the development of more bio-sustainable conventional arable cropping practices (delivering improvements to yields, margins and soil systems) has been demonstrated in long term system experiments in the UK e.g. Stobart & Morris (2011). However, variation in response, together with implementation cost and crop management issues, are common reasons why cover cropping approaches are not more widely adopted. This suggests the need for improved understanding of which approaches are more likely to deliver benefits / disbenefits in particular scenarios. In addition the research by Stobart and Morris did not specifically consider the value of cover crops as weed management tools; to this end this work substantially augments our understanding of the grower benefits delivered through the use of cover crops. Specifically, a better understanding of species selection and the development of suitable species mixtures for particular scenarios could improve both performance and accessibility of cover cropping. The recent review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species carried out for AHDB (White et al. 2016) highlighted the need to have a better understanding of the impacts of cover crops on weeds and this study addreses that gap directly.

The Achilles heel of black-grass is its short term persistence in the seedbank; a figure of 70% is generally used as a ball park figure for the annual decline rate. It is also a weed that is adapted to emerge predominantly in the autumn with a much smaller flush in the spring. Against this background, contrasting arguments are made for the pros and cons of cover cropping compared with the use of a chemical fallow. On the one hand, it is claimed that cover crops suppress weed emergence and growth which is interpreted as being a good thing. Conversely, others argue that using a chemical fallow allows multiple cultivations that can flush more seed from the seedbank, which can then be killed with glyphosate. It is, therefore, unclear whether cover cropping has a net negative or positive impact on black-grass populations. Here we have integrated field studies with a weed competition model, which has been parameterised and evaluated for black-grass and 11 legume species within the LegLINK mix (Storkey & Cussans, 2007; Storkey et al. 2011) to allow extrapolation of the findings to a wider range of circumstances and to consider the key underlying mechanisms driving field-observed effects.

The objectives of the project were therefore to:

1. Quantify the effect of different cover cropping approaches on weed populations and seed return in following crops compared with conventionally managed autumn and spring cropping and fallowing.
2. Evaluate the potential for plant residues to suppress weed establishment and growth in a wider range of grass weed species and compare a wider range of cover crop species.

Building on this work, if cover crops are shown to be an important tool in an integrated weed management strategy,

3. Develop agronomy and management guidelines for the use of cover cropping within integrated weed management.
4. Evaluate the use of cover cropping within integrated weed management and detail their likely influence on system profitability.
5. Improve understanding of the effects of such approaches on wider parameters (e.g. soil systems and measures of biodiversity) and the better integration of ecosystem services into conventional crop production systems.

3. Materials and methods

3.1. Field trials to evaluate the impact of cover cropping on black-grass populations.

3.1.1. Field trial design

The focus of the experiment is on the efficacy of the different systems in suppressing populations of black-grass. A series of field experiments was therefore established at two contrasting field sites with large populations of black-grass on both a heavier soil type (clay loam) and on lighter land (sandy loam).

The experiments included three ‘conventional treatments’:

1) a first and second winter wheat with best practice herbicide applications
2) a spring crop following an over-winter fallow managed for optimal weed control and a following winter wheat
3) a twelve month bare fallow managed for optimal weed control followed by a winter wheat crop.

In eight further treatments different cover crops were trialled as either a short-term (over-winter) cover followed by spring wheat, preceding winter wheat or a long-term (year long) cover preceding a winter wheat. The cover crops were:

a) biofumigant brassica,
b) conventional brassica,
c) white clover,
d) LegLINK mix. The LegLINK mix was an optimal species combination based on data from the LegLINK project (e.g. Figure 1) and output of the weed competition model at Rothamsted and included white clover, lucerne and black medick.

This design was considered carefully (Figure 2) and where the range of cover crops are included gives a total of 11 treatments which provides the maximum number of comparisons while maintaining the statistical power of the trial with the resources available. With 4 replicates, there were 44 plots in total. Large plot sizes were used (12 x 6 m).

Full treatment list (2012 and 2013):

1. Conventional winter wheat (‘business as usual’)
2. Spring wheat
3. Conventional un-cropped fallow
4. Short-term cover-crop: Biofumigant brassica (Vitasso)
5. Short-term cover-crop: Conventional brassica
6. Short-term cover-crop: LegLINK designed mix
7. Short-term cover-crop: White clover
8. Long-term cover-crop: Biofumigant brassica (Vitasso)
9. Long-term cover-crop:Conventional brassica
10. Long-term cover-crop:LEGLINK designed mix
11. Long-term cover-crop: White clover

Cover crops were established in late September 2012 and in early September 2013. For the trial established on the sandy loam soil in Spetember 2013, the short-term overwinter legume cover crops followed by spring cereals (Treatments 6 & 7), which had failed in 2012, were replaced with spring-sown legume cover crops following overwinter stubble/fallow to match the treatments resulting from the management changes in the 2012 trial.

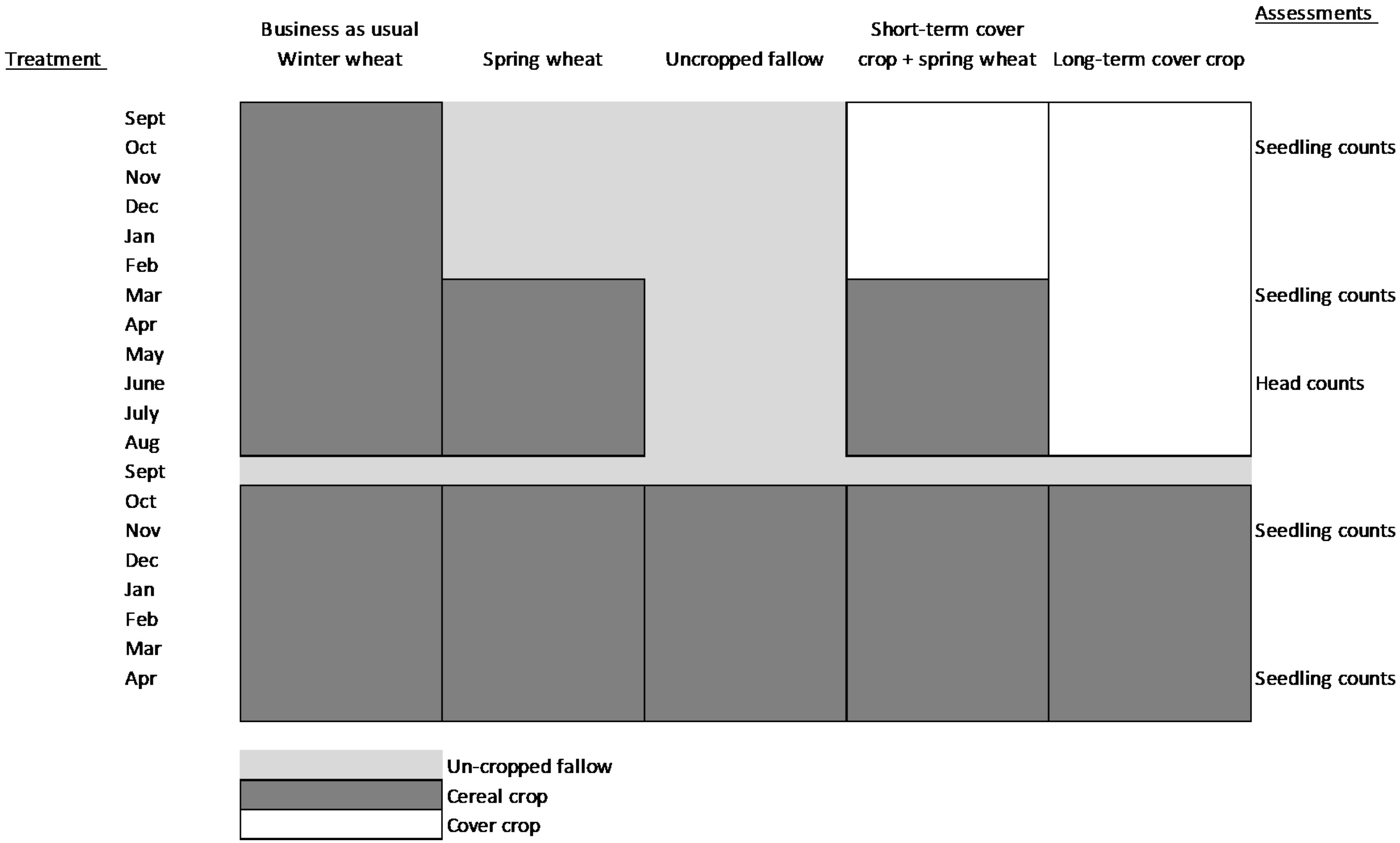

Figure 2. Schematic illustrating how cover crops might be incorporated into a cereal rotation over two growing seasons compared with three conventional treatments. The full range of cover-crops tested are described in the text. Black-grass assessment timings also shown.

For the trial established in September 2014, the treatment detail was changed so that the cover crops and management approaches used better reflected the new CAP Greening rules, as agreed by the AHDB project management group. Because of the difficulties in reliably establishing cover crops on the clay loam site, this work was carried out on the sandy loam site only, where establishment of cover crops was carried out in early September. No new trial was established on the clay loam site.

Treatment list (2014)

1. Winter Wheat (Control)
2. Winter wheat with broadcast oats (sprayed off in spring)
3. Over-winter bare fallow followed by spring wheat
4. Over-winter bare fallow (frequent cultivation; at least 3x) followed by spring wheat
5. Over-winter cover crop (oats + vetch) followed by spring wheat
6. Over-winter cover crop (rye + vetch) followed by spring wheat
7. Over-winter cover crop (rye + vetch + crimson clover) followed by spring wheat
8. Over-winter bare fallow followed by spring white clover
9. Over-winter bare fallow followed by spring LegLINK mix
10. 12 month bare fallow (minimal cultivation)
11. 12 month bare fallow (frequent cultivation)
12. 12 month cover crop (oats + vetch + white clover)
13. 12 month cover crop (oats + vetch + LegLINK mix)

3.1.2. Field trial assessments

The focus of the assessments was on the black-grass weed at different stages in its life cycle. Weed seedling density was assessed in October / November and March / April to capture autumn and spring emerging cohorts and head density was assessed in the early summer to quantify seed return (Figure 2). Seedlings were also counted in the following crop to provide data on long-term population dynamics. In later trials, yield and ground cover were also assessed.

3.1.3. Data analysis

Data were collated and checked in Excel. Black-grass data (seedling and head numbers) were very rarely normally distributed and hence, where needed, the data were log-transformed for analysis of variance. The data have been re-transformed for presentation with means of plots/assessments shown with standard errors wherever this doesn’t make the presentation over complex.

3.2. Field trial on cover crop establishment

Significant problems were encountered during the field trials programme in establishing cover crops effectively, in particular smaller-seeded legume species on the heavier (clay loam) field trial site. In the final year (2015/16 season) an additional trial was carried out on the clay loam site with significant black-grass weed pressure to compare different approaches to cover crop establishment (Table 1) to help identify the priorities for cover crop establishment and the consequences of differences in establishment for the weed pressure in following spring crops (here spring barley). No herbicides were used in the spring barley. Black-grass populations were measured after establishment of the spring barley (9th May 2016) and black-grass heads were counted in early July (5th July 2016).

Table 1. Cover crop establishment trial treatment table

Establishment method	Drilling date	Cover crop
Broadcast onto stubble	Early September	LegLINK mix
		LegLINK mix + rye
		Rye + vetch
		Wheat seed
Cultivated and drilled with plot drill	Early September	LegLINK mix
		LegLINK mix + rye
		Rye + vetch
		Wheat seed
Broadcast onto stubble	Early October	LegLINK mix
		LegLINK mix + rye
		Rye + vetch
		Wheat seed
Cultivated and drilled with plot drill	Early October	LegLINK mix
		LegLINK mix + rye
		Rye + vetch
		Wheat seed
Cultivated bare fallow	n/a	None
Over-winter stubble	n/a	None

3.3. Modelling the impact of cover cropping on the dynamics of black-grass populations.

We combined a population dynamics model with a model of weed competition and seed production to investigate the net effect of the role of cover crops on black-grass seedbank density, allowing the effect of cover crops in suppressing weed emergence and growth to be integrated and compared with the role of a chemical fallow which allows multiple cultivations that can flush more seed from the seedbank which can then be killed with glyphosate. This work built on stochastic models being developed at Rothamsted. Stochastic models models incorporate naturally occuring randomness associated with events within the model, for example in weather conditions. This means they produce different results every time the model is run. This allows the strength of the management signal on black-grass dynamics to be interpreted in the context of the background uncertainty associated with variability in parameter estimates and weather inputs.

3.3.1. Model description

The life cycle of an annual weed is relatively straightforward to model, requiring three functions that describe the emergence of seedlings, production of fresh seed and seed losses from the soil surface and soil seedbank (Storkey et al., 2015).

Seedling emergence

The proportion of the soil seedbank that emerges following a soil disturbance event will be a product of the time of year, weather, condition of the seedbed, age of the seedbank and the distribution of seeds in the soil profile. We modelled this process in three steps.

The first step used a stochastic approach to modelling the maximum potential of the seedbank to produce seedlings (E_{max}) following a cultivation event. In so doing, we acknowledge that it is very difficult to model all the interactions of seasonal variation in seed dormancy, weather and soil conditions that determine the size of the weed flush in a given year. Rather we sampled from a probability distribution of weed emergence derived from empirical data observed over five sites and three years, Figure 3.

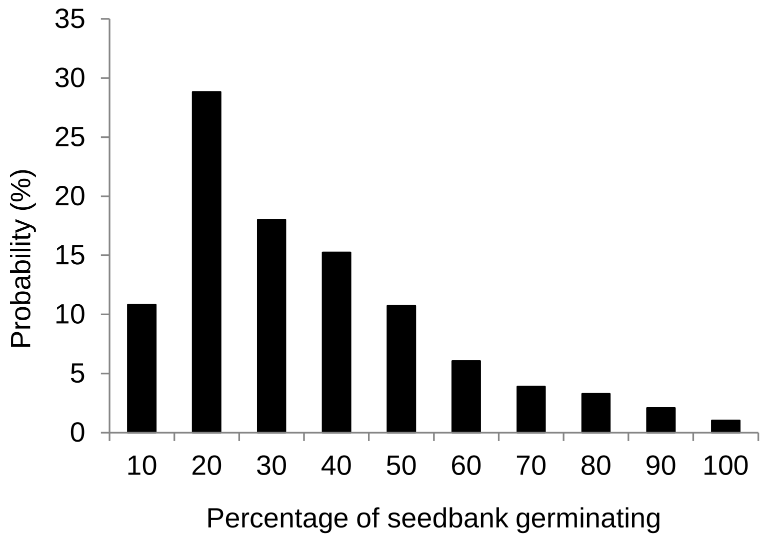

Figure 3. Probability distribution for black-grass emergence based on three years' data from five sites (Storkey et al., 2003).

The second step was to reduce the probability of emergence of seeds lower down the soil profile for each model run. We assumed that emergence of seeds in the top 2cm of the soil profile was not limited by depth but, below this depth, the chances of a seed making it to the surface declined linearly – the maximum depth for black-grass emergence is approximately 8cm. This function was used to reduce E_{max} depending on the distribution of seeds in the soil profile ($E_{max,\ depth}$). The seeds that did not germinate were assumed to have induced dormancy and remain in the seedbank. A proportion of the seeds that emerged from depth (15%) were lost to lethal germination (Benvenuti et al., 2001). For our purposes, we assumed an even distribution of seed through the soil profile, but the model has the capability to model different scenarios, where seed might be concentrated in the upper layer and therefore the model can be used to examine the consequences of different soil mixing events more fully.

The third step was to take account of the germination calendar for black-grass. To do this a 'slice' was taken of the germination calendar between the sowing date and the end of the autumn flush. The area under this slice of the curve (Figure 4) was then calculated and used to further reduce $E_{max,\ depth}$ in response to a change in sowing date, $E_{max,\ depth,\ date}$. Adjustments of E_{max} in this way allow the model to more accurately represent the number of seedlings that would be present in a crop and captures the impact of delayed drilling and the use of a stale seedbed. It can also be further reduced to reflect any inhibition of weed germination by a cover crop.

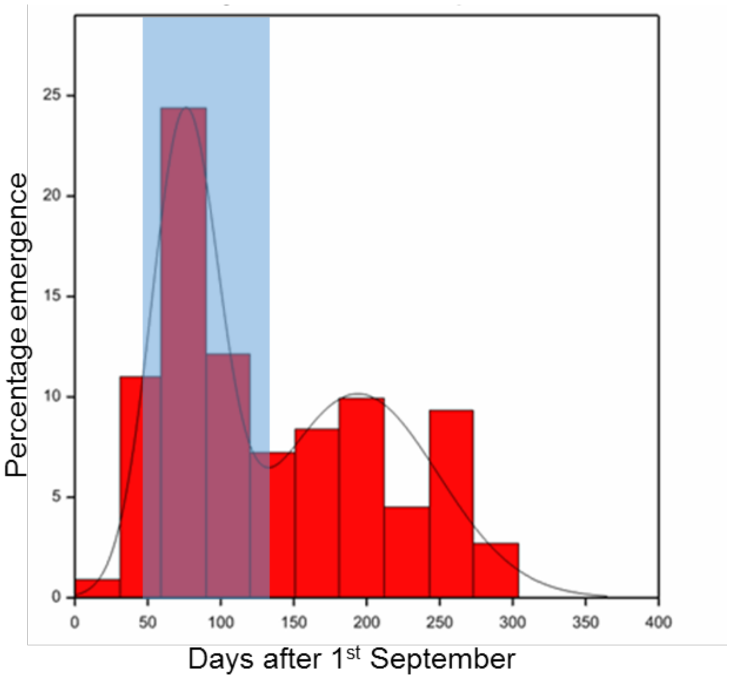

Figure 4. Typical germination calendar for black-grass (red bars) with a smoothed curve function fitted. This is used to calculate the effect of delayed drilling so that the percentage emergence for any drilling date is estimated using a 'slice' (blue box) taken between drilling date (here 15th October) and the end of the autumn flush (8th January).

Fresh seed production

Complete control of black-grass in autumn cereals is now very difficult and we assume that a proportion of weed seedlings emerging in an autumn crop (5%) survive to produce fresh seed – this figure for herbicide mortality can easily be adjusted within the model. Weed competition and fecundity of survivors are impacted by sowing date, crop seeding rate and weather. A mechanistic, weather driven crop / weed competition model has been developed at Rothamsted that captures all of these factors and this was used to predict mature weed biomass in autumn crops (Figure 5). The model was run using meteorological data from 20 years (1997-2016) to capture the effect of variable weather on weed growth and seed production (Andrew and Storkey, 2017). The allometric relationship between mature biomass and seed production was then used to predict fresh seed production.

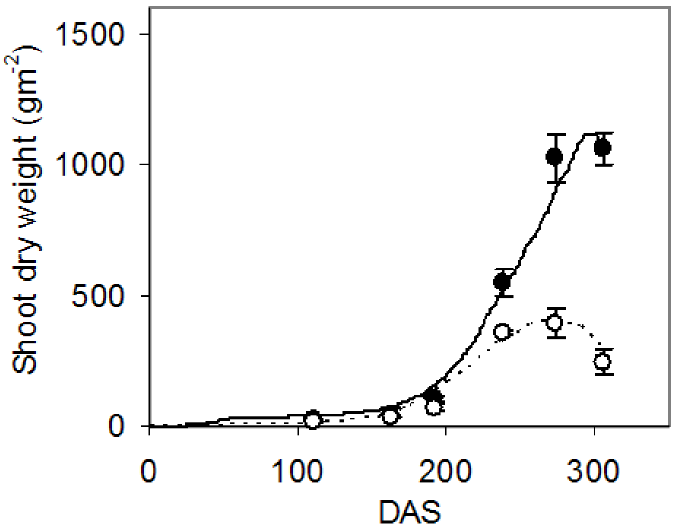

Figure 5. Example of output from competition model validated against empirical data for growth of winter wheat (● observed, —— predicted) and weeds (○ observed, - - - - predicted) (Storkey and Cussans, 2007), DAS = Days After Sowing. Maximum weed shoot biomass was used to predict seed production.

The competition model has been built for winter wheat cultivars emerging in the autumn; much less work has been done on black-grass competition in spring crops. However, data are available from the AHDB project RD-2009-3647 ('Sustaining winter cropping under threat from herbicide-resistant black-grass (*Alopecurus myosuroides*))' on the relationship between black-grass density and head production in both winter and spring crops assessed in the same years (Figure 6). Because of the shorter period of vegetative growth, black-grass produces fewer heads / plant when emerging in the spring. This reduction in black-grass fecundity was used to predict seed return in a spring sown crop. Year to year variation in weather will also be less important for a spring crop and, therefore, median values were used for the simulation runs up to the beginning of March. The lack of data on the populations dynamics of black-grass in spring crops is currently a knowledge gap in the model but it is reasonable to assume there will be some seed return albeit at a reduced rate than in a winter crop.

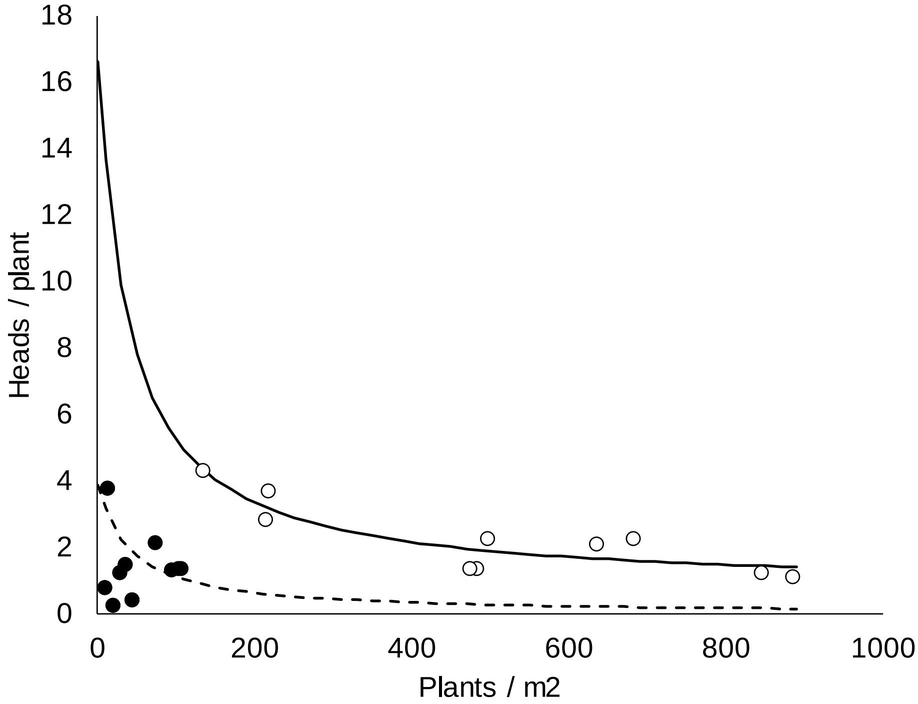

Figure 6. Observed relationship between black-grass density and head production for weeds in autumn emerging (○) and spring emerging crops (●) from AHDB project RD-2009-3647 (Sustaining winter cropping under threat from herbicide-resistant black-grass (*Alopecurus myosuroides*)). A hyperbolic curve was fitted to the autumn data and the intercept adjusted to reduce head production for spring emerging weed cohorts. This proportional reduction in black-grass fecundity was used to adjust predicted seed return in spring crops.

Seed losses

As with total emergence, the losses of fresh seed through predation and other sources of mortality are very variable year to year. We therefore modelled this process stochastically, using a frequency distribution for seed losses derived from a meta-analysis of multiple seed predation experiments (Davis et al., 2011); a normal distribution was used with a mean of 0.52 and a standard deviation of 0.05. The seeds that don't germinate in a given year remain in the seedbank and decline at an exponential rate. While a figure of 70% per year is often quoted as the annual decline rate of black-grass seedbanks, we again sampled from a frequency distribution that reflected the range of values in the literature (45 – 80%); for example, Lutman et al. (2003) observed a consistent decline rate of 45-51% for two populations of black-grass assessed at two sites.

3.3.2. Model validation

To validate the model it was compared with the classic black-grass population dynamics model published by Moss (1990). This model is empirical and deterministic and uses a single value to model each step of the life cycle described above. Although simple, it has been used to demonstrate the relative impact of different cultivation practices on the black-grass seedbank. Our model runs did not include soil inversion and so we compared the output to the scenario in the Moss study with very shallow cultivation and baled straw (as opposed to straw burning) using the same starting point of 20 seeds m^{-2} in the top soil layer. The Moss model predicted a maximum annual rate of increase of the seedbank in the absence of herbicides of 15x; the rate of increase declines as weed densities increase because of competition between weed individuals (Figure 7). The more complex, mechanistic model that we developed in this project, reflected the build-up of weed populations (Figure 7). In our approach we ran the model each time using a different combination of E_{max}, seedbank decline rate and seed losses sampled for the frequency distributions; a total of 1000 runs. This 'stochastic' approach captures the uncertainties associated with trying to predict weed population dynamics (Freckleton and Watkinson, 2002) and illustrates the danger of using a deterministic model to predict the impact of changes in management. The advantage of our stochastic approach is that we can interpret the strength of any management signal in the context of this background uncertainty.

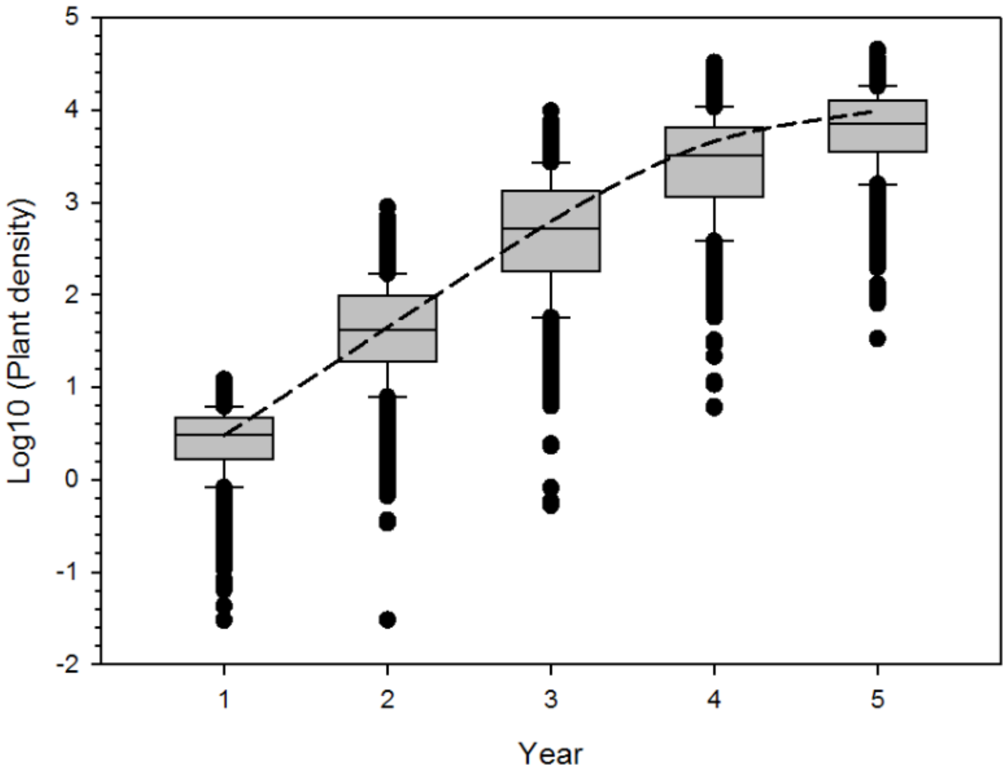

Figure 7. Output of model predicting increase in the black-grass seedling density (m^{-2}) in the absence of herbicides. The dashed line plot is the prediction from the Moss model with direct drilling and baled straw using a single value for each parameter in the model (Moss, 1990). The more complex model outputs are for minimum cultivation. These are presented as box and whisker plots where each year shows the output of 200 model runs (each with a unique combination of $E_{max, depth, date}$, weed competition, seed production, rate of seedbank decline and losses of fresh seed sampled from frequency distributions). The middle line of each box = median value and the boundaries represent the 25th and 75th percentile. Whiskers represent the 10th and 90th percentile with outliers indicated by ●.

3.4. Assessment of biofumigation impacts on grass-weed species

The literature review allowed the identification of a range of candidate Brassica species that might be grown as biofumigant cover crops (Table 2). The most active biofumigant isothiocyanate (ITC) concentrations are highest when are plants ‘harvested’ immediately before flowering, and have the most potential effect when incorporated rapidly as fresh materials.

Table 2 Candidate biofumigant species listed in descending order of typical concentration of isothiocyanate (ITC) with variety used in the experiments

Crop species	Common name	Variety used
Eruca sativa L	Arugula / Rocket	Trio
Brassica nigra	Black mustard	
Brassica juncea	Brown / oriental /Indian mustard	Pacific Gold
		Vitasso
Sinapis alba	Yellow / white mustard	Idagold
		Smash
Brassica napus	Oilseed rape	Excaliber
Raphanus sativus	Radish	Doublet
		Bento
Triticum aestivum	Wheat (used as a control)	Santiago

Biofumigant crops were grown in 20 L pots in the greenhouse. In the screening experiment, the equivalent of 1 Kg m^{-2} freshly-harvested residues were pre-mixed with the top 5 cm of loam soil in each 20 L pot. Four replicate pots of each treatment were established and un-germinated black-grass seeds were added to the surface and mixed to 2 cm. The seed was allowed to germinate and grown for 8 weeks in an unheated glasshouse, when the black-grass foliage was harvested, dried and weighed. Data were transformed (log) for analysis of variance.

Petri-dish germination tests were also carried out using fresh extracts from the biofumigant crop residues. The residues were soaked in water and roughly strained to give a 'dirty liquid'. 5 ml of the liquid was added to the petri dish at the start and germination tests then carried out with black-grass seed. 5 replicates were used for each treatment. . Data were transformed (log) for analysis of variance.

In 2013/14 a screening experiment was carried out for a wider range of grass weed species using the biofumigant mustard (Vitasso), which had been demonstrated to have some effect in the previous study. Two replicate screening experiments were carried out, the equivalent of 1 Kg m^{-2} freshly-harvested residues were pre-mixed with the top 5 cm of loam soil in each 20 L pot. Four replicate pots were sown of each grass weed / crop species: *Alopecurus myosuroides, Anisantha sterilis, Avena fatua, Brassica rapa, Bromus commutatus, Lolium multiflorum, Triticum aestivum*. The seed was allowed to germinate and grown for 8 weeks in an unheated glasshouse, when the weed foliage was harvested, dried and weighed. . Data were transformed (log) for analysis of variance.

4. Results

4.1. Field trials to evaluate the impact of cover cropping on black-grass populations

4.1.1. Trials established September 2012

Autumn 2012 was wet and followed an exceptionally wet summer. As a consequence ground conditions were not ideal at the end of September (and had not been better earlier) and establishment of the legume cover crops was poor at both sites.

At the sandy loam site, black-grass seedling numbers in late winter were high and not significantly different between the treatments (Figure 8). At this stage, the establishment of the legume cover crops was so poor that it was decided to re-drill the plots so that an effective ground cover could be established.

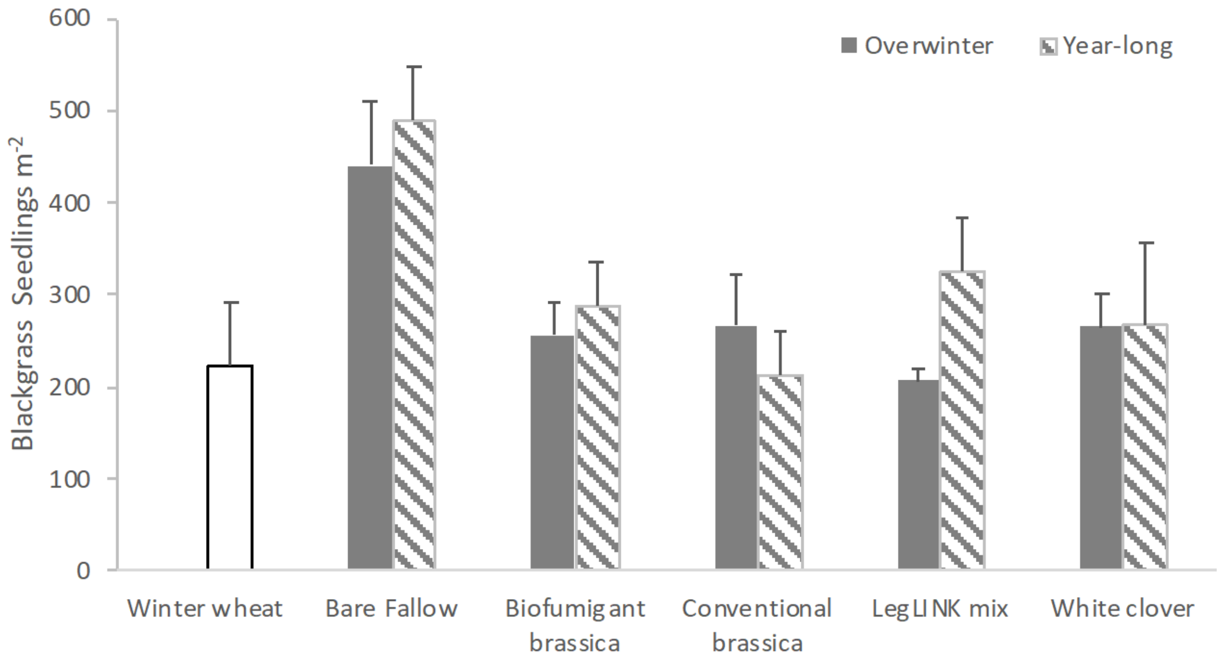

Figure 8. Spring observation (20/21st March 2013) of black-grass seedling density following establishment of the cover crops on a sandy loam soil. Bars are means of four replicate plots with standard error of the mean shown. For treatment details see Section 3.1.1

Establishment of all cover crops was challenging on the clay loam, the seedbed conditions on these heavy soils lead to very variable establishment between treatments and as expected there was very significantly greater ground cover achieved by the mustard species in the autumn (Figure 9). More numerous populations of black-grass seedlings were seen in the autumn in all the cover crop treatments (with no differences between the cover crops) and where the ground was left as bare fallow compared with the winter wheat, which had received pre-emergence herbicide (Figure 10). In other trials work, carried out in parallel, using cover crops on the same site, we observed that early drilling (late August – early September) meant that black-grass often out-competed the cover crops; however, if cover crops were established later (mid-September – mid-October) to reduce the weed burden, establishment was poor, often due to wet and sticky seedbed conditions.

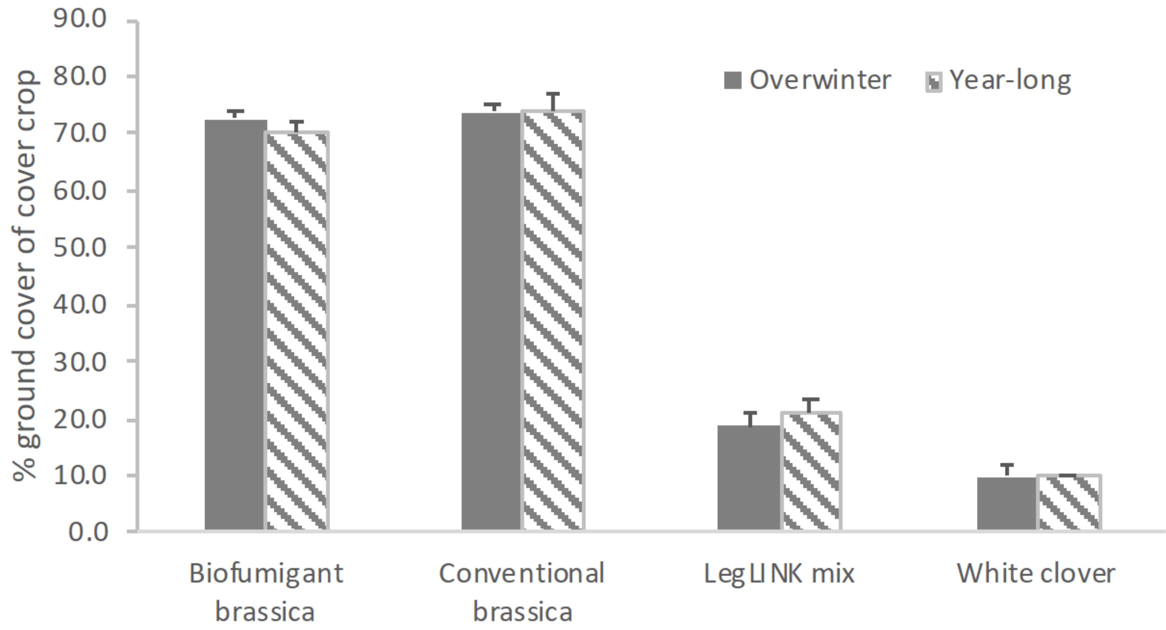

Figure 9. Ground cover (visually assessed in early winter) following establishment of the cover crops on a clay loam soil. For treatment details see Section 3.1.1. Bars are means of four replicate plots with standard error of the mean shown.

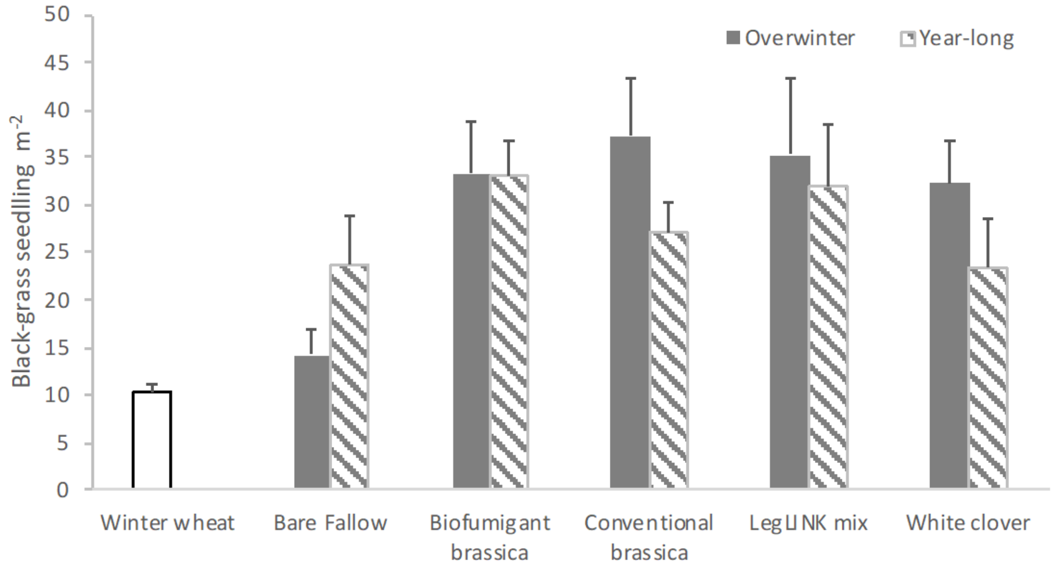

Figure 10. Autumn observation (5th November 2012) of black-grass seedling density following establishment of the cover crops on a clay loam soil. Bars are means of four replicate plots with standard error of the mean shown. For treatment details see Section 3.1.1

In the summer, black-grass head density was much lower in all plots that had received spring cultivations (Figures 11 and 12). Weed control in spring wheat on the sandy loam soil, was very effective; in contrast, black-grass control at this site for winter wheat had not been effective as no pre-emergence herbicide had been applied. There was a significant population of black-grass and hence the potential for a significant seed return during the year-long cover crops or fallow treatments. In a commercial situation mowing or total herbicide would be used in the year-long treatments to prevent seed return. At the clay loam site there was a positive benefit of the year-long cover crops in reducing the number of black-grass heads in the early summer compared with the fallow; the reverse was seen on the sandy loam site. There were no significant differences in observed black-grass populations between the biofumigant and conventinonal mustard cover crops.

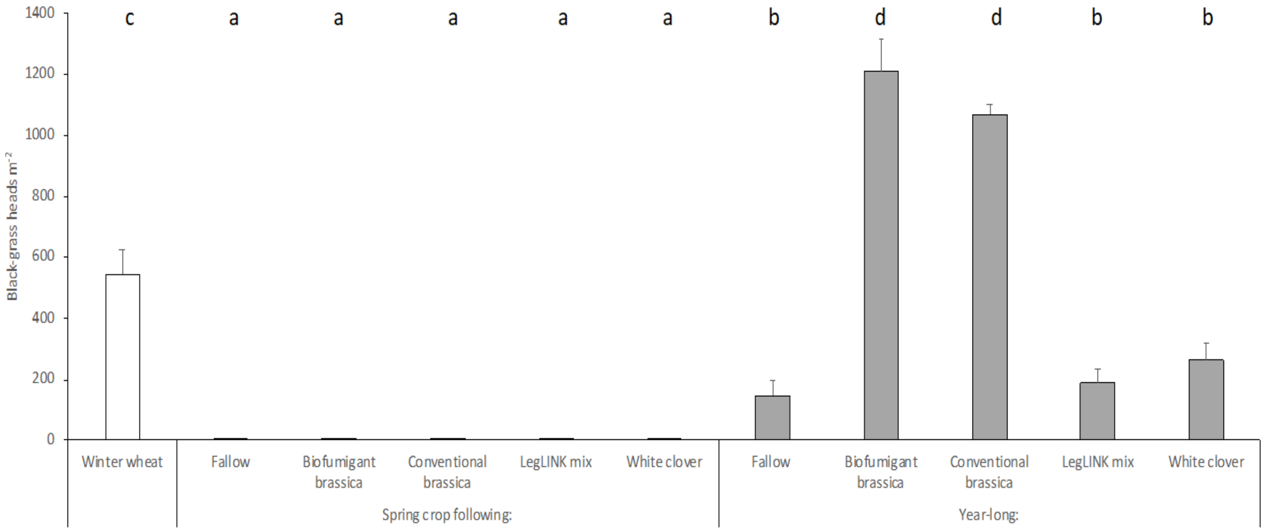

Figure 11. Black-grass head counts on the sandy loam soil (June 2013). Bars are means of four replicate plots with standard error of the mean shown. For treatment details see Section 3.1.1 ; the year-long LegLINK and white clover cover crops were resown in spring 2013 after poor autumn establishment. Letters above bars indicate statistically significant differences. Treatments sharing a letter do not differ at the 5% significance level.

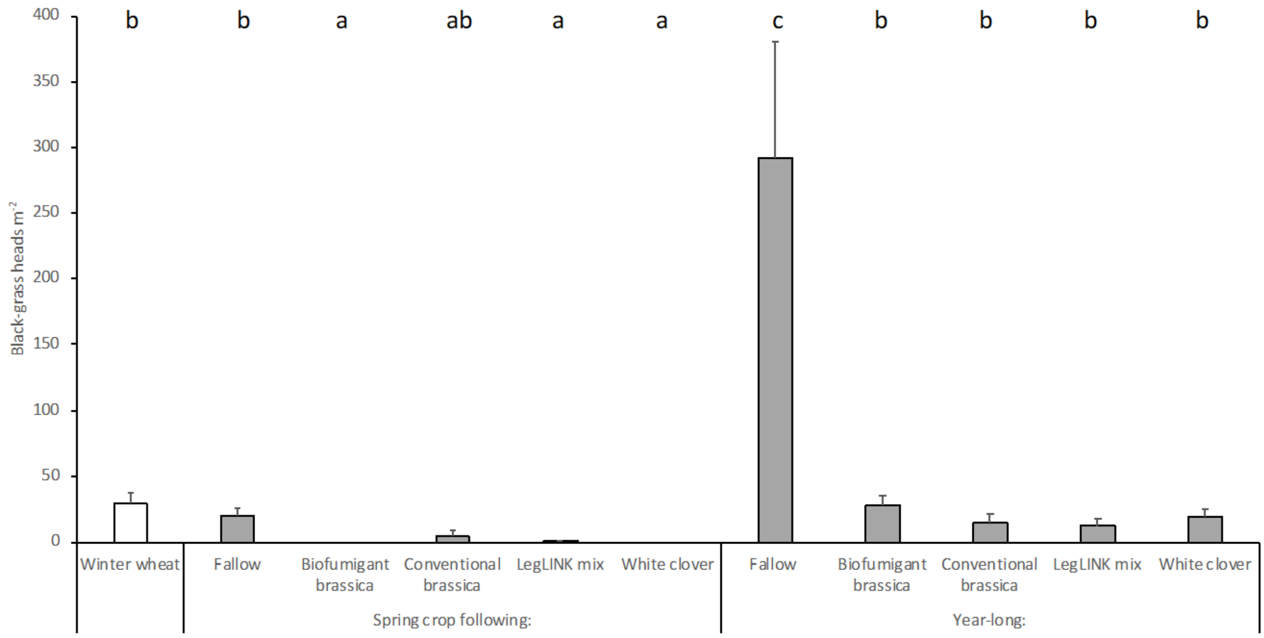

Figure 12. Black-grass head counts on the clay loam soil (June 2013). Bars are means of four replicate plots with standard error of the mean shown. For treatment details see Section 3.1.1 Letters above bars indicate statistically significant differences. Treatments sharing a letter do not differ at the 5% significance level.

4.1.2. Trials established September 2013

The trial on the clay loam again suffered from poor cover crop establishment despite early September sowing. Ground cover of cover crops was less than 10% in spring. This trial therefore provided no evidence to help examine the value of cover crops as a tool in weed control and no further results are reported here.

On the sandy loam soil, the herbicide programme for winter wheat was more effective in 2013 than it had been in 2012, and no black-grass seedlings were seen in the late winter observation. Larger and variable black-grass seedling populations were seen in late winter in all the cover crop treatments and where the ground was left as bare fallow, compared with the winter wheat, but there were no significant differences in black-grass seedling populations between these treatments (Figure 13). Establishment of the autumn-sown cover crops and the ground-cover achieved by the cover crop was also very variable between plots; where the LegLINK mix was sown there was more consistent cover achieved by the cover crop – but the contributing species varied between plots.

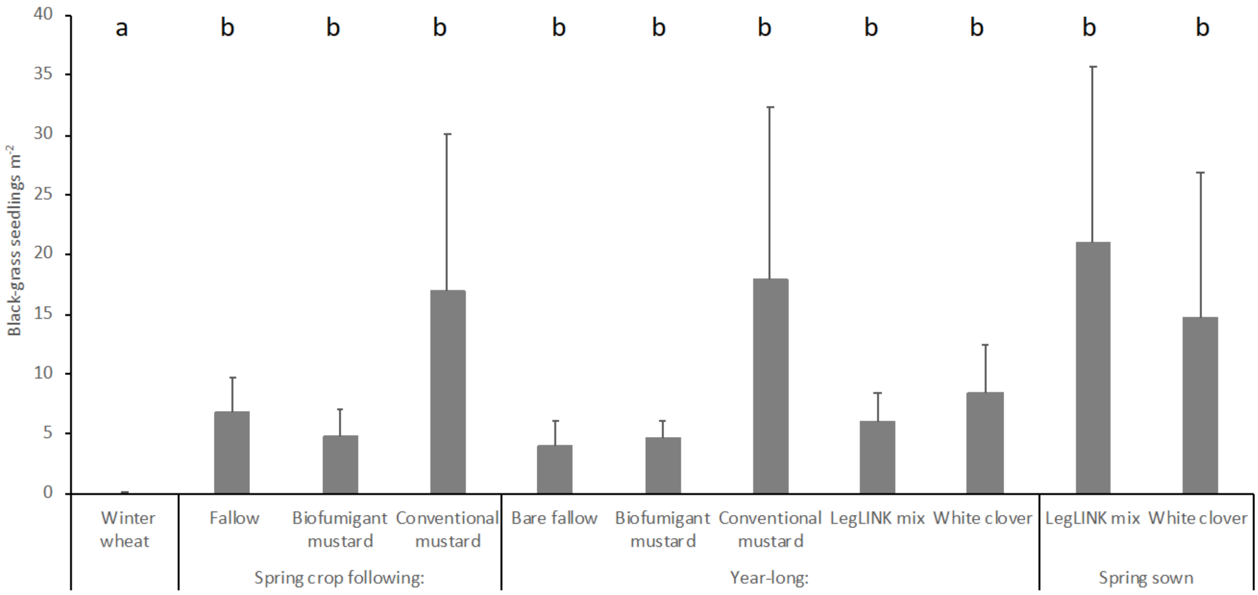

Figure 13 Late winter observation (3rd February 2014) of black-grass seedling density following establishment of the cover crops on a sandy loam soil. At the time of this observation the spring-sown plots were bare fallow and the over-winter cover crops were still present. Bars are means of four replicate plots with standard error of the mean shown. For treatment details see Section 3.1.1. Letters above bars indicate statistically significant differences. Treatments sharing a letter do not differ at the 5% significance level.

There is no regrowth of the year-long mustard cover crops following mowing in late spring, hence when the ground cover of the year-long cover crops was assessed in summer 2014, in the bare fallow and mustard cover crops there was a large proportion of bare ground and a significant spring-germinating weed population (Figure 14). The spring-sown legume-based cover crops gave a fully canopy of the sown cover than the same mixes sown in the autumn (Figure 14). In the bare fallow, spring cultivation had allowed control of black-grass, however there was a significant blackgrass population in all the year-long cover crops (Figure 15). Observations in the field noted that these were largely immature and could have been further controlled with an additional mowing in a commercial situation. The winter wheat and all the spring-sown crops and cover crops had low head numbers of black-grass (Figure 15).

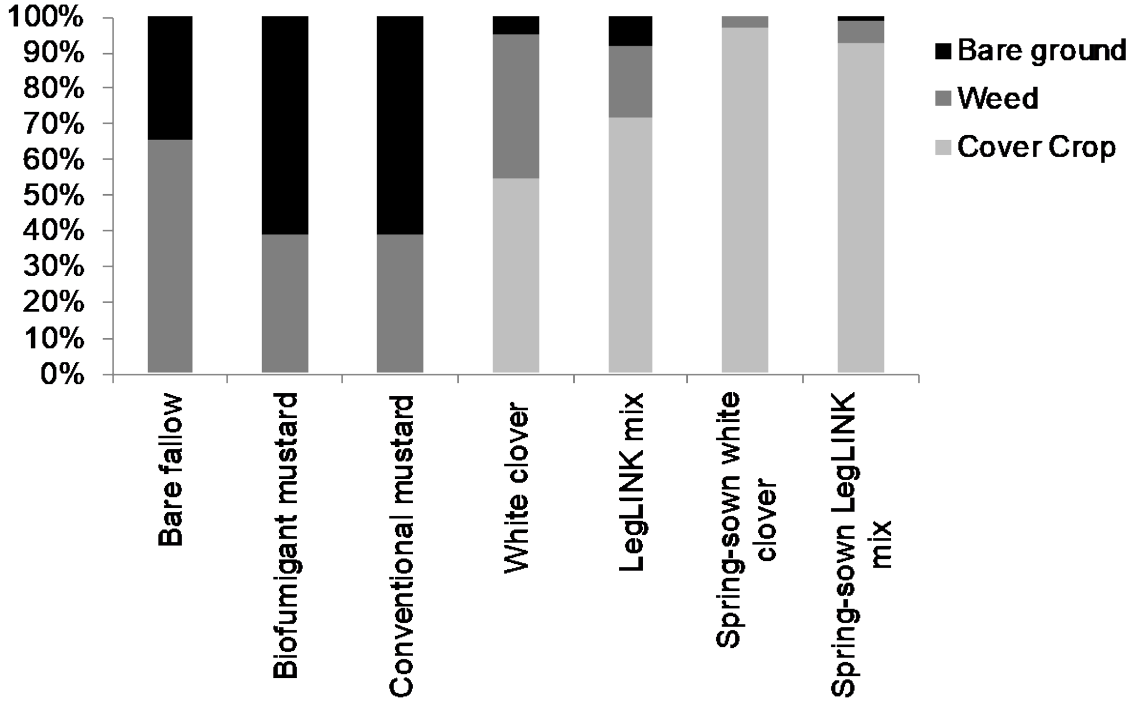

Figure 14 Ground cover of year-long cover crop species (unless otherwise indicated) compared with bare fallow on sandy loam soil (13th August 2014).

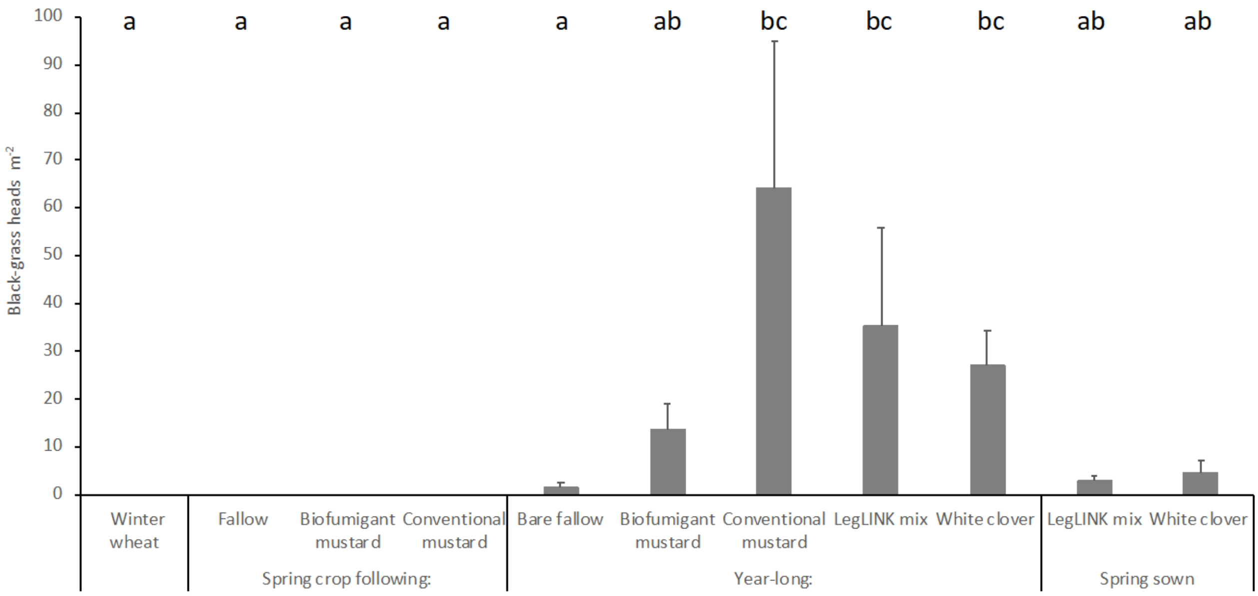

Figure 15 . Summer observation (13th August 2014) of black-grass head numbers following establishment of the cover crops on a sandy loam soil. Bars are means of four replicate plots with standard error of the mean shown. For treatment details see Section 3.1.1. Letters above bars indicate statistically significant differences. Treatments sharing a letter do not differ at the 5% significance level.

In the following winter wheat crop (established following inversion tillage), black-grass seedling density measured in late-winter ranged from 4-10 seedlings per m^2 and differences between the preceding treatments were small (and non-significant). However, the final hand-harvested yields showed very significant but small (0.5 t ha^{-1}) increase in yield where winter wheat followed immediately after a year-long cover crop treatment (whether spring or autumn established) compared with a preceding winter wheat, spring wheat or fallow (Figure 16). The main yield component affected was ear number with 590 on average following cover crops and 560 in the other treaments.

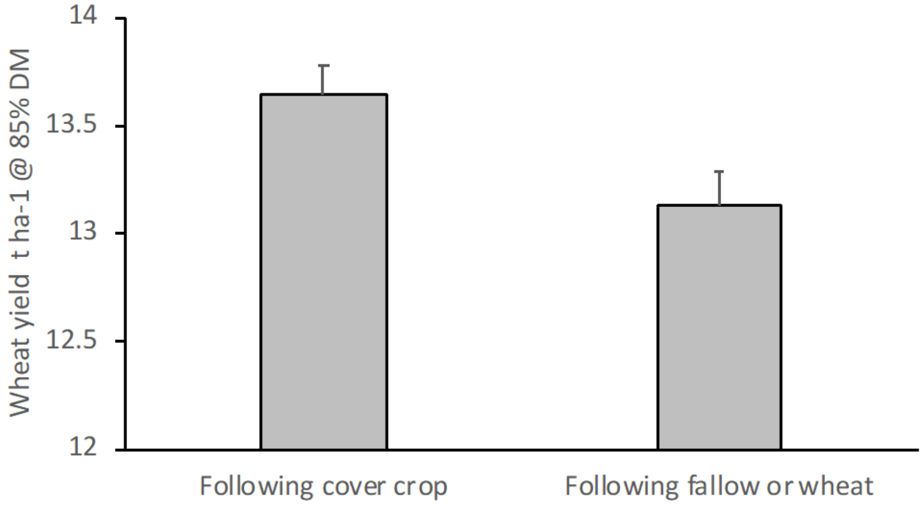

Figure 16. Hand-harvested yield of winter wheat (August 2015) following a range of cover crop and fallowing treatments established in September 2013 on a sandy loam soil. Bars are means of four replicate plots with standard error of the mean shown. For treatment details, see Section 3.1.1.

4.1.3. Trials established September 2014 – new cover cropping treatments

On the sandy loam soil, the herbicide programme used for winter wheat was relatively ineffective in controlling black-grass. As a result, variable black-grass seedling populations were seen in late winter in all the treatments, but there were no significant differences in black-grass seedling populations between these treatments (Figure 17). The autumn-sown cover crops with oats and vetch had established well, however, there was no (significant) reduction in black-grass seedling numbers compared with the overwinter fallow or winter wheat crops.

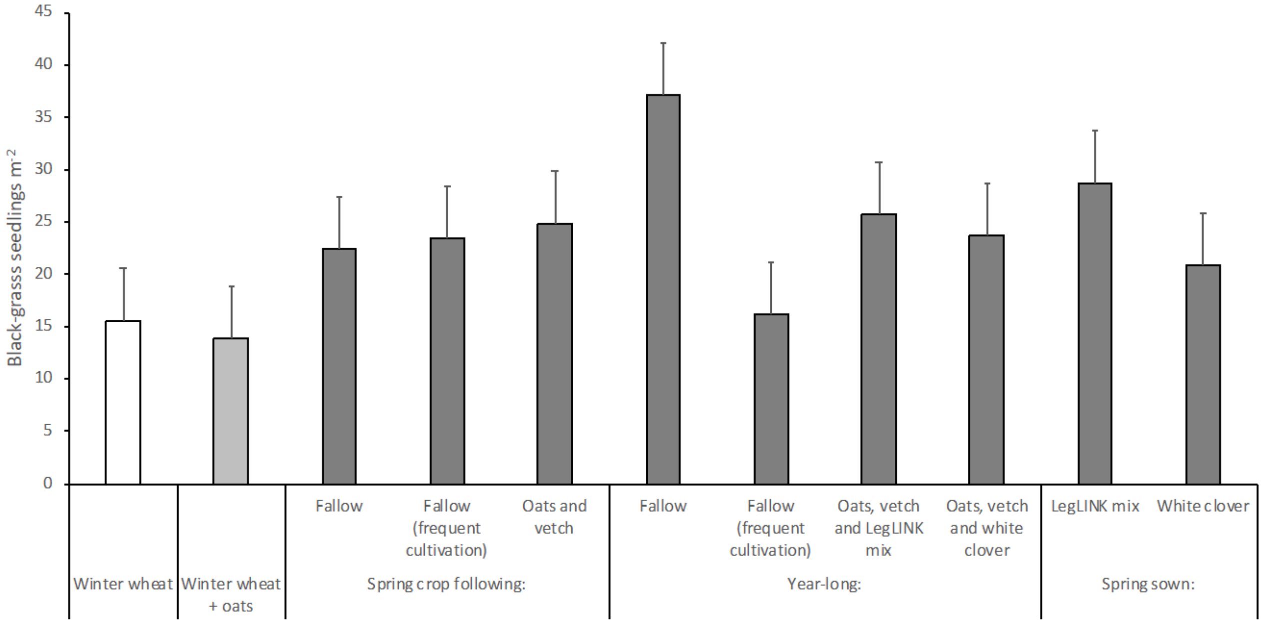

Figure 17. Spring observation (17th March 2015) of black-grass seedling density following establishment of the cover crops on a sandy loam soil. At the time of this observation all the fallow plots had been maintained in the same way, the spring-sown plots were bare fallow and the over-winter cover crops were still present. Bars are means of four replicate plots with standard error of the mean shown. For treatment details see Section 3.1.1. Letters above bars indicate statistically significant differences. Treatments sharing a letter do not differ at the 5% significance level.

When the ground cover of the cover crops was assessed in summer 2015, the oats and vetch based over-winter covers were shown to have persisted well (Figure 18). In the bare fallow and spring-sown cover crops, ground-cover was dominantly spring weeds with some bare ground. In this year the LegLINK mixture did not establish as well as the white clover cover crop.

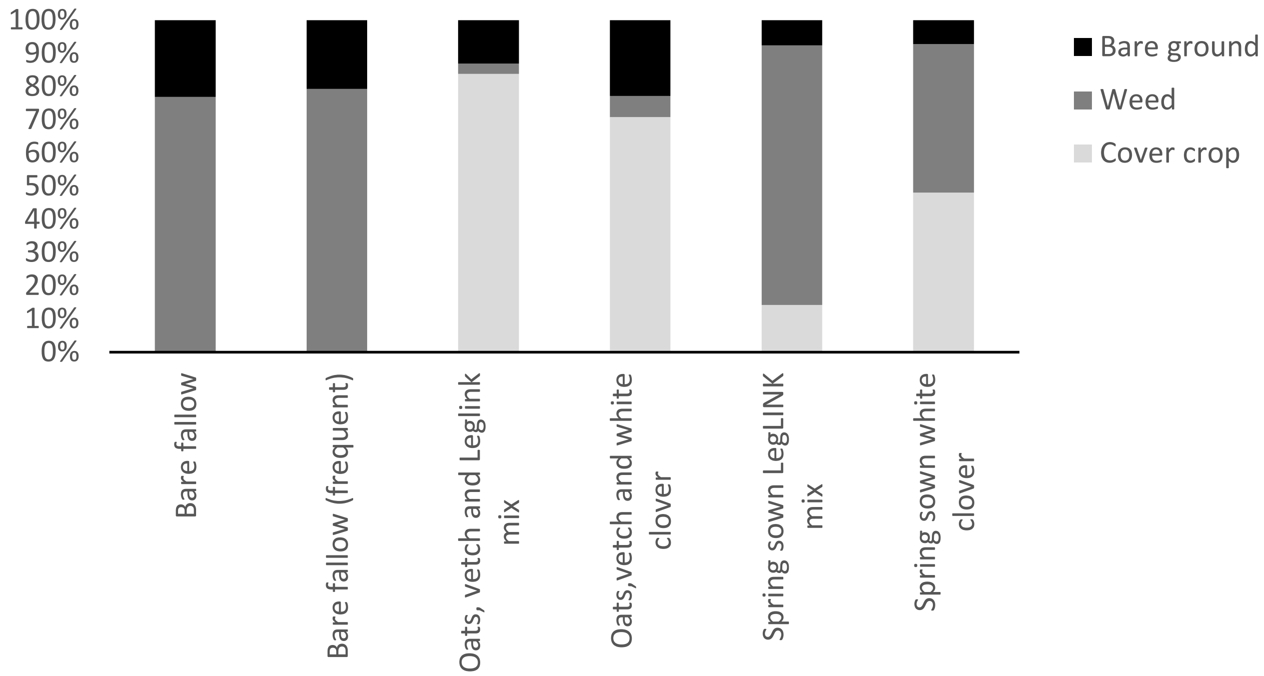

Figure 18 Ground cover of cover crop species (unless otherwise indicated) compared with bare fallow on sandy loam soil (mid-August 2015).

Where spring cultivation had occurred, especially where spring wheat was grown, black-grass head-numbers were significantly lower in the summer, however there was a large blackgrass population in all the the year-long cover crops (Figure 19). The winter wheat crops had the highest head numbers of black-grass in August because of the failure of weed control in the autumn; autumn-sown cover crops had slightly (but not significantly lower) head numbers of black-grass compared with the winter wheat crops (Figure 19).

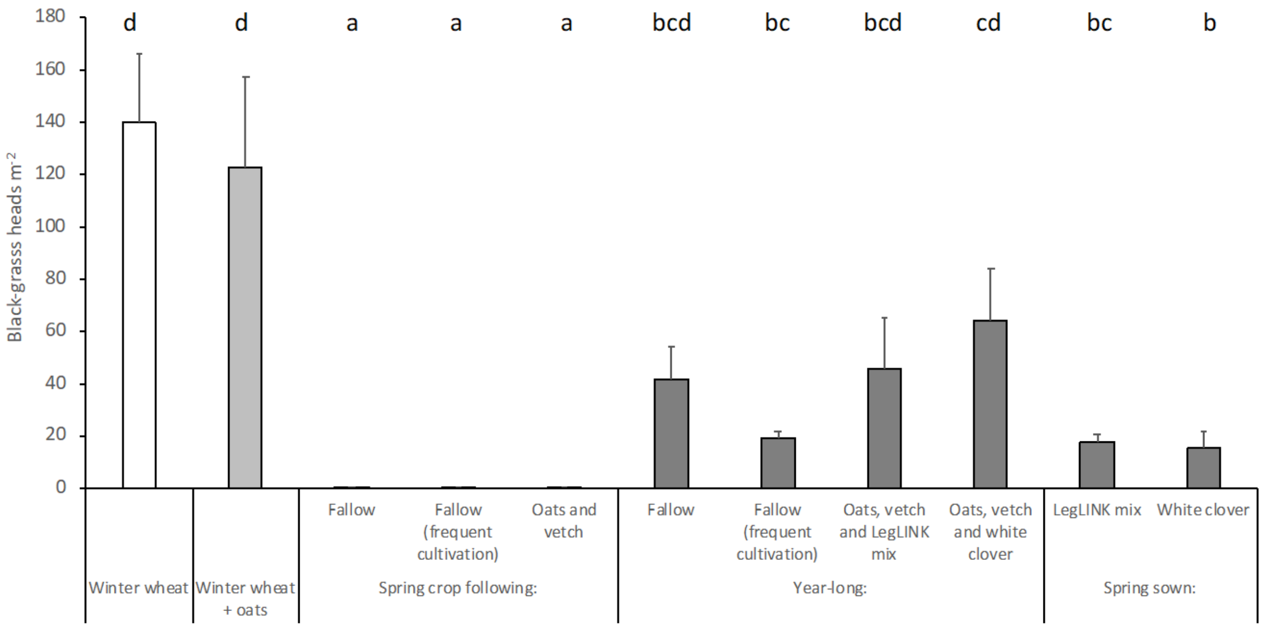

Figure 19. Summer observation (mid-August 2015) of black-grass head numbers following establishment of the cover crops on a sandy loam soil. Bars are means of four replicate plots with standard error of the mean shown. For treatment details see Section 3.1.1. Letters above bars indicate statistically significant differences. Treatments sharing a letter do not differ at the 5% significance level.

In the following winter wheat crop, there were significant differences between some of the preceding treatments in the observed black-grass seedling density measured in late-winter (Figure 20). The differences are strongly positively correlated with the black-grass head numbers observed in August (Figure 21). The black-grass could not be controlled adequately in the winter wheat and hence the trial was destroyed in late spring.

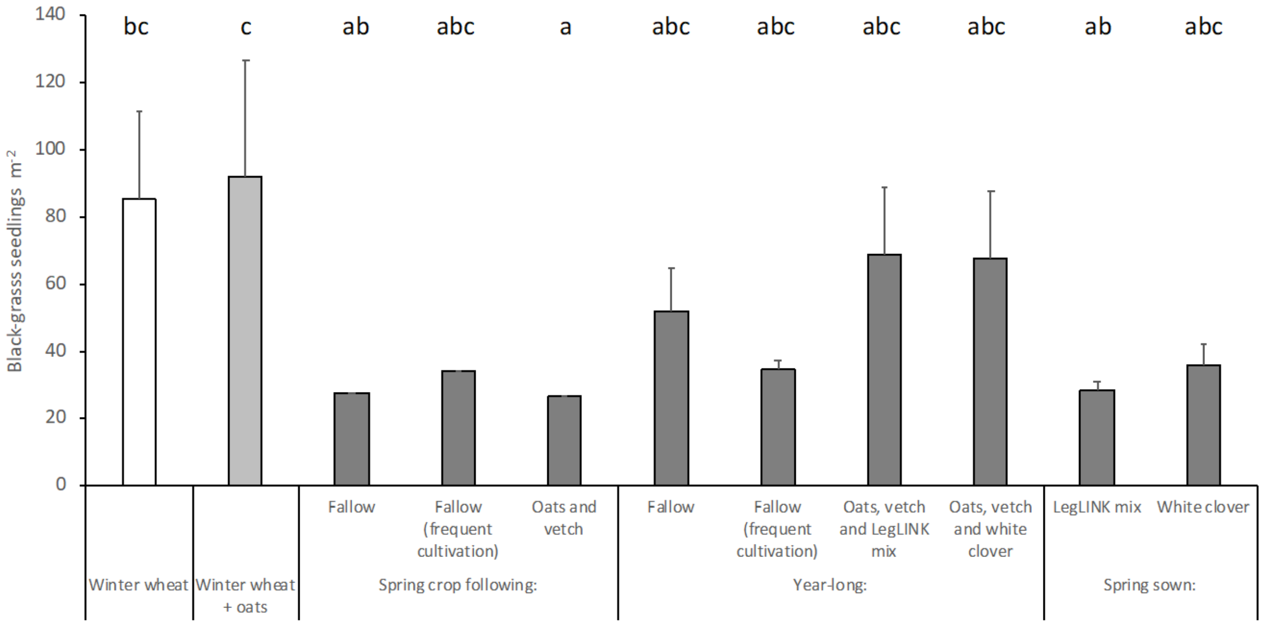

Figure 20 Late-winter observation (22nd February 2016) of black-grass seedling density following establishment of the winter wheat crop following all treatments on a sandy loam soil. Bars are means of four replicate plots with standard error of the mean shown. For treatment details see Section 3.1.1. Letters above bars indicate statistically significant differences. Treatments sharing a letter do not differ at the 5% significance level.

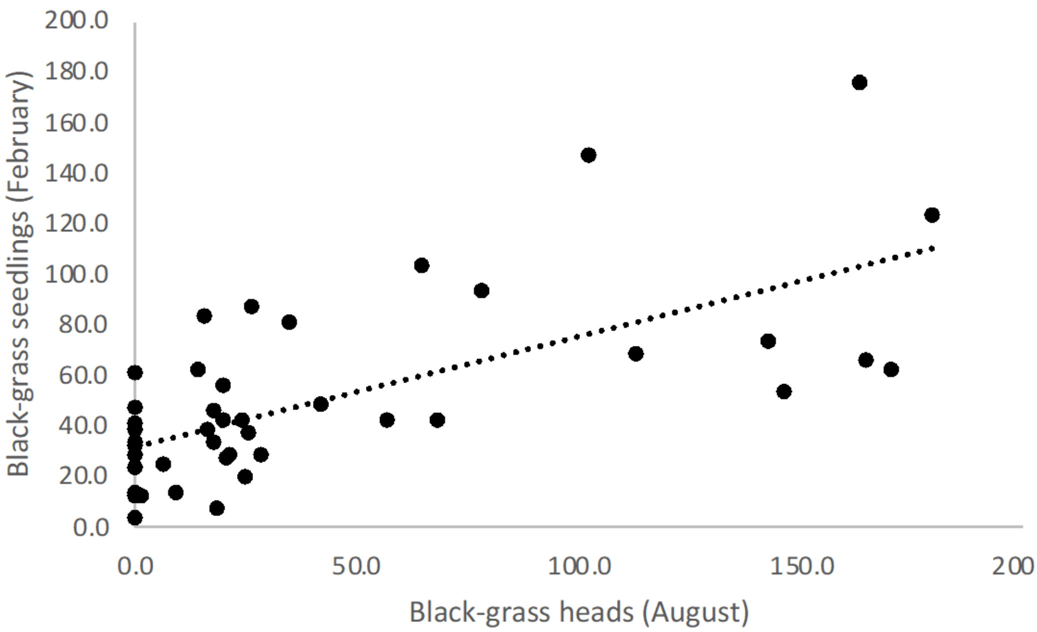

Figure 21 Black-grass seedling density (22nd February 2016) in winter wheat plotted against the black-grass head numbers measured in August 2015 following the treatments on a sandy loam soil. Individual plot data shown as points with the line of best fit (R^2 = 0.4436)

4.2. Field trial on cover crop establishment – clay loam soil (2015/16)

On the heavy clay loam soil there were no significant differences in the cover measured where cover crops had been established in early September either by broadcasting on stubble or drilling following cultivation and no signficant differences between cover crop species. However, where cover crops were established in early October, there was a much higher % cover obtained in February 2016 where cover crops had been drilled compared with broadcasting for all cover crops (Figure 22). There was also a much bigger difference between cover crop species, with legumes showing poor establishment at the later sowing date, whereas drilled cover crops of rye and vetch or wheat and beans had the highest ground cover when drilled at the later sowing date.

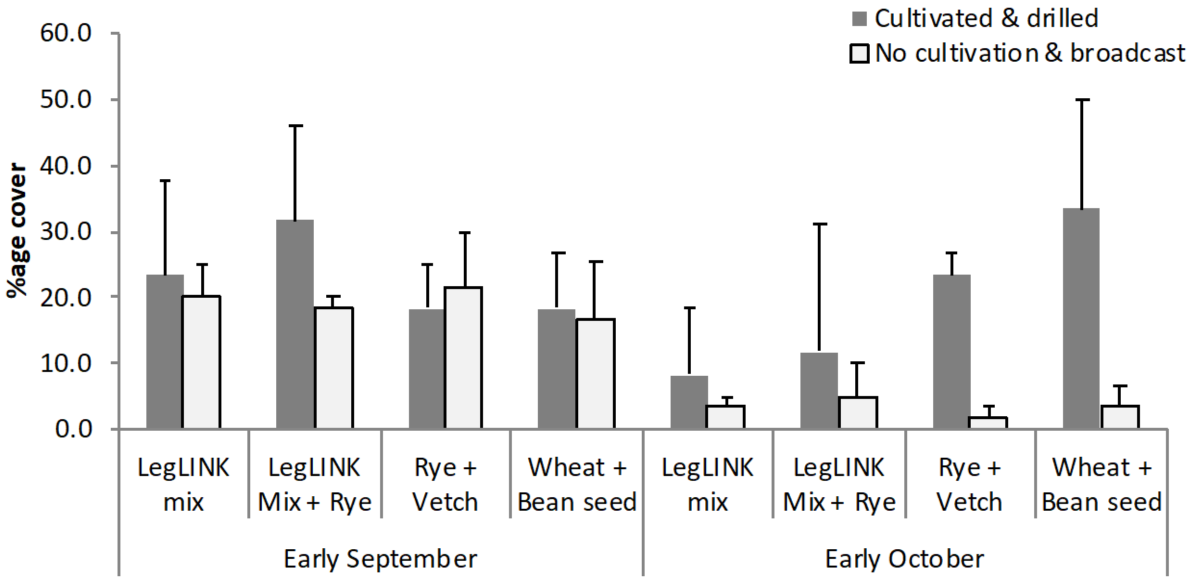

Figure 22. Percentage ground cover of the cover crops measured in February 2016 when established at different dates (early September vs early October) and by different methods (broadcast vs drilling). Bars are means of three replicate plots with standard error of the mean shown.

The highest density of black-grass heads was measured in spring barley following all the treatments where seed had been broadcast onto stubble after minimal preparation with a straw-rake in Setember (no cultivation & broadcast, Figure 23) with no significant difference between cover crops and/or where no crop was sown. Where cover crops had been sown in October, there were slightly fewer black-grass heads in the spring barley (but not significantly different) where plots had been fully cultivated and drilled (Figure 23) but again there was no significant difference between cover crops and/or where no cover crop was sown. As expected the number of black-grass heads measured in the spring barley in July was strongly correlated with the number of black-grass seedlings measured in the newly-established crop in May (Figure 24).

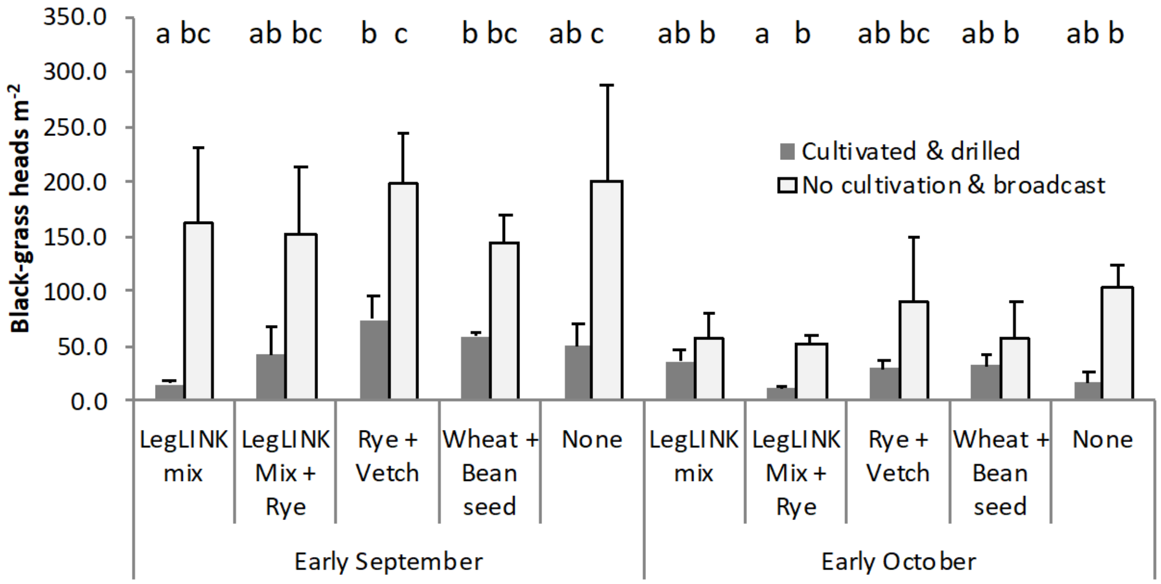

Figure 23. Black-grass heads in the spring barley crop (July 2016) following a range of cover cropping approaches. Bars are means of three replicate plots with standard error of the mean shown. Letters above bars indicate statistically significant differences. Treatments sharing a letter do not differ at the 5% significance level.

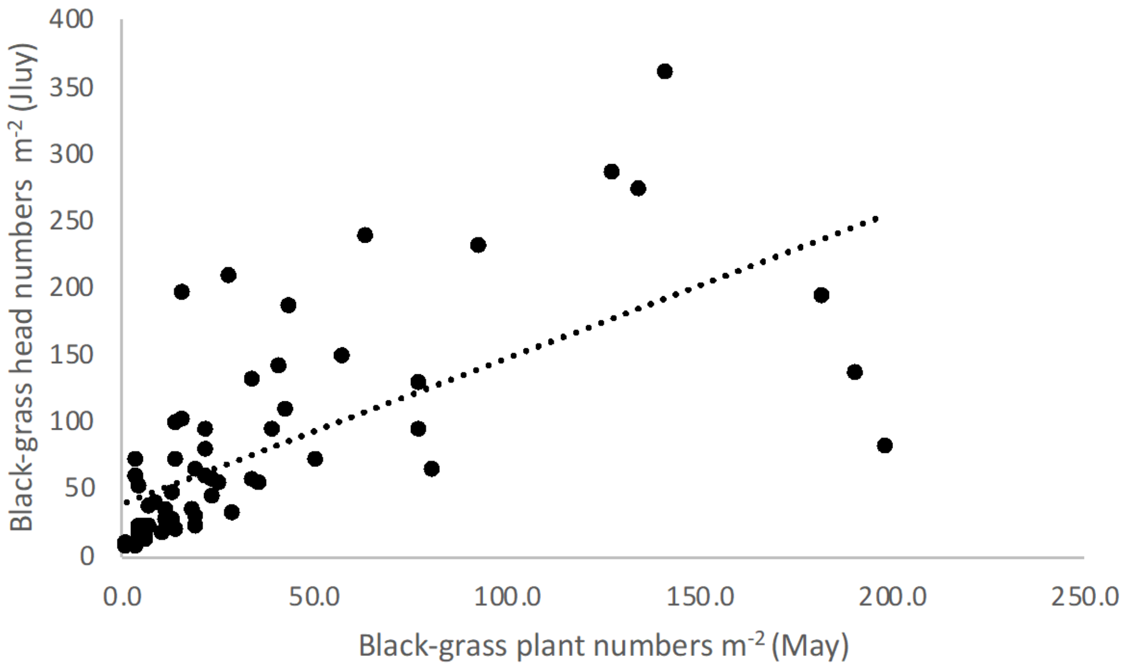

Figure 24. Black-grass head numbers (July 2016) in spring barley plotted against the black-grass seedling density measured in May 2016 following a range of cover cropping treatments. Individual plot data shown as points with the line of best fit (R^2 = 0.4363)

4.3. Modelling the impact of cover cropping on the dynamics of black-grass populations.

4.3.1. Model scenarios

The model was used to quantify the balance between weed seed bank decline in the soil, suppression by a cover crop and losses through the use of a stale seedbed with repeated cultivations. The reference scenario was an autumn winter wheat crop sown on 1st October with a crop density of 300 plants m^{-2}. It was assumed that the combination of residual and contact herbicides controlled 95% of the weed seedlings emerging after drilling (Scenario 1 in Figure 25). In this case, although the median value from the 1000 model runs indicated an overall decline in the weed seedbank (by 28%) assessed in the following autumn, there was high variation and in 17% of the cases, the seedbank increased (Figure 26).

Scenarios 2-4 (Figure 25) represent different options for an over-winter fallow followed by a spring crop. In each case, we assume there will be some seed return in the crop although the density of seedlings and seed production / weed plant will be lower than in a winter crop. In all cases where there was an overwinter fallow, a large reduction in the black-grass seed bank in the following autumn was predicted. This is mainly due to the shape of the emergence calendar (Figure 4) that means the larger autumn cohort can be controlled in the fallow with fewer weed seedlings left to emerge in the crop. In addition, the shorter growing period means the weeds that do emerge and survive the herbicide produce less seed.

In Scenario 2, the stubble is cultivated in the autumn, stimulating a weed flush that is then sprayed off with glyphosate (100% control) prior to the preparation of the seedbed for the following spring crop (with the accompanying spring weed flush). In Scenario 3, two additional cultivations of the over winter stubble are simulated. Each time, additional weeds are flushed out of the seedbank using the frequency distribution for E_{max} each time (Figure 3). The numbers of weeds emerging after each successive over winter cultivation decreases because of the shape of the emergence calendar (Figure 4). Multiple stubble cultivations did have an additional small beneficial effect, further depleting the weed seedbank (Figure 26). A disadvantage of establishing a cover crop on the over winter stubble (Scenario 4) is that this opportunity for multiple cultivations is lost. The model therefore predicted a similar outcome to a chemical fallow with a single cultivation event. We also incorporated the possible inhibitory effect of a cover crop on weed emergence in this scenario by reducing $E_{max, depth, date}$ by a further 20%. This had the effect of increasing the size of the predicted weed seedbank in the following autumn by a very small amount.

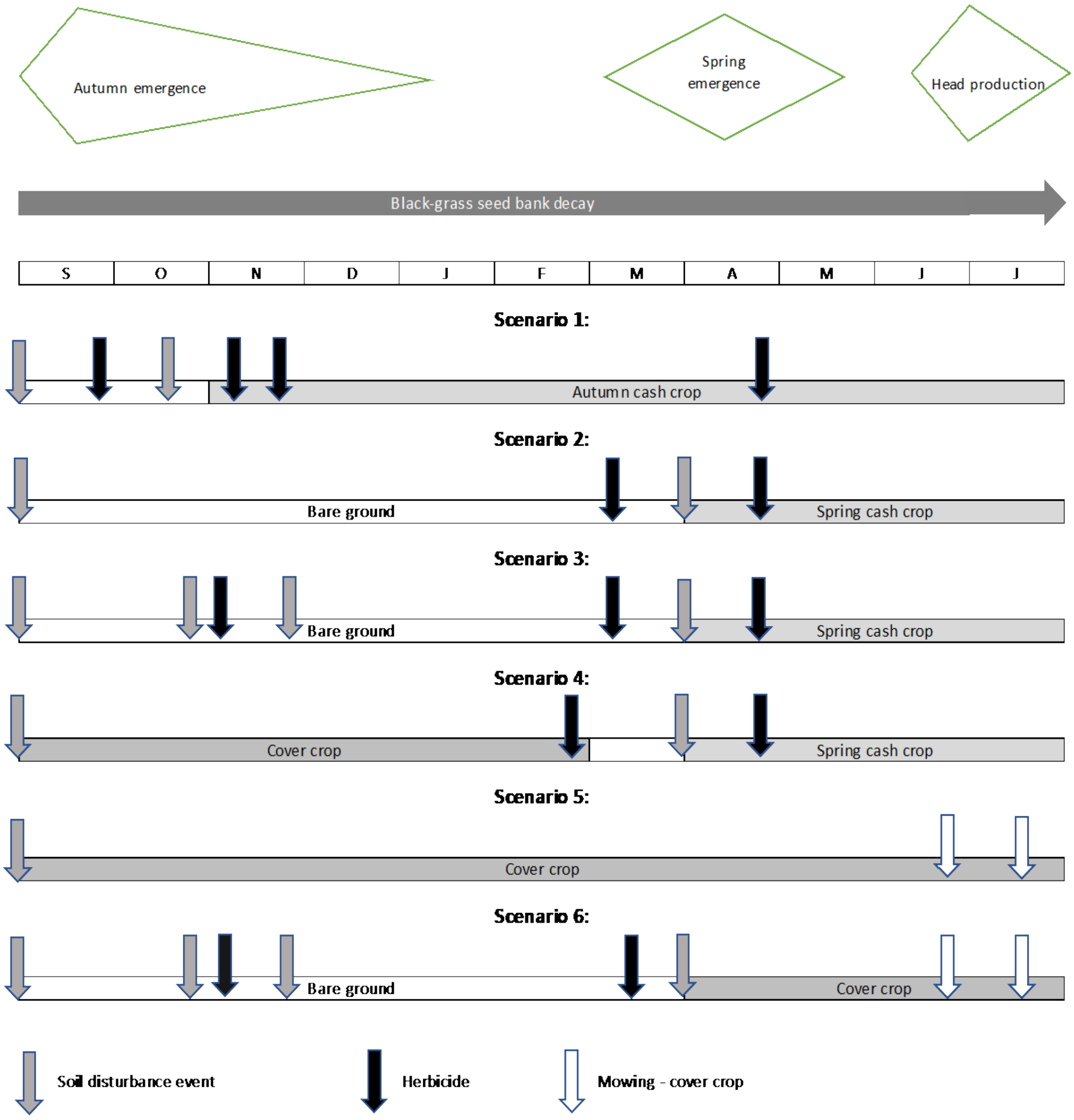

Figure 25. Key stages in the annual black-grass life-cycle shown by month with schematic diagrams to illustrate the six scenarios used to model the impact of management of black-grass population dynamics.

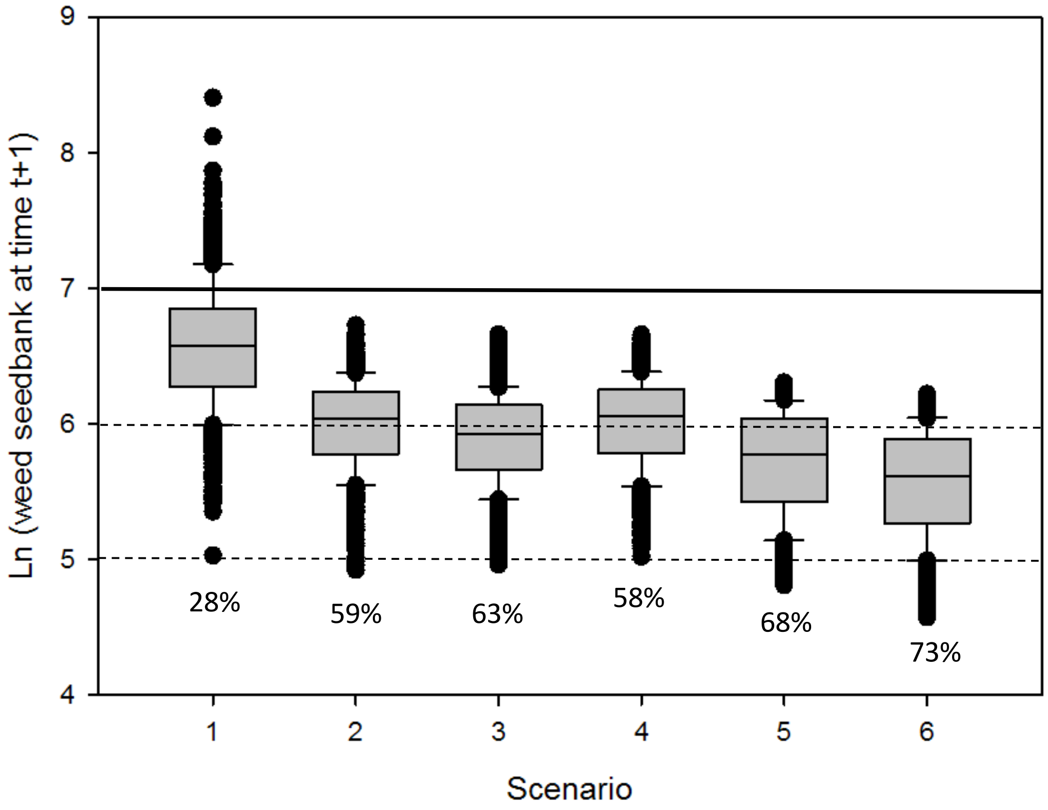

Figure 26. Modelled black-grass seedbank (presented as natural log, Ln). Output of model for six scenarios illustrated in Figure 23. In each case, the model has been run 1000 times incorportaing stochasticity in weed emergence, competition, seed production, seedbank decline and losses of fresh seed. The middle line of each box is the median value for each scenario and the boundaries of each box represent the 25th and 75th percentile. Whiskers represent the 10th and 90th percentile with outliers indicated by ●. All points above the solid horizontal line (Ln of 1000 seeds in the initial seedbank) represent an increase in the weed seedbank and all points below a decrease. The median value is also shown as a percentage reduction in the seedbank below the plotted values.

In Scenarios 5 & 6, the field is taken out of production for a whole 12 months (Figure 25). This is a rare practice in commercial arable systems but would provide an opportunity to both to control annual weeds and build soil fertility. In this case, it is assumed that there is no seed return as black-grass would be controlled by mowing and smothered by re-growth of the cover crop. Consequently, Scenarios 5 & 6 result in the best weed control giving a reduction in the weed seedbank of 68 and 73% respectively (Figure 26). The difference between scenarios 4 & 5 is purely down to the stimulation of the spring weed flush and some seed return in the crop.

4.4. Assessment of biofumigation on grass-weed species

4.4.1. Effects on black-grass of different residues

The largest reduction in early growth of black-grass (22.4%) was seen where rocket residues were incorporated (variety Trio; Figure 27); other ITC containing species (Table 2) also reduced black-grass foliage significantly compared with the un-amended control. However, the incorporation of fresh wheat residues (variety Santiago) also reduced the early growth of black-grass. The residues of radish had no (Doublet) or a similar effect (Bento) to the wheat control.

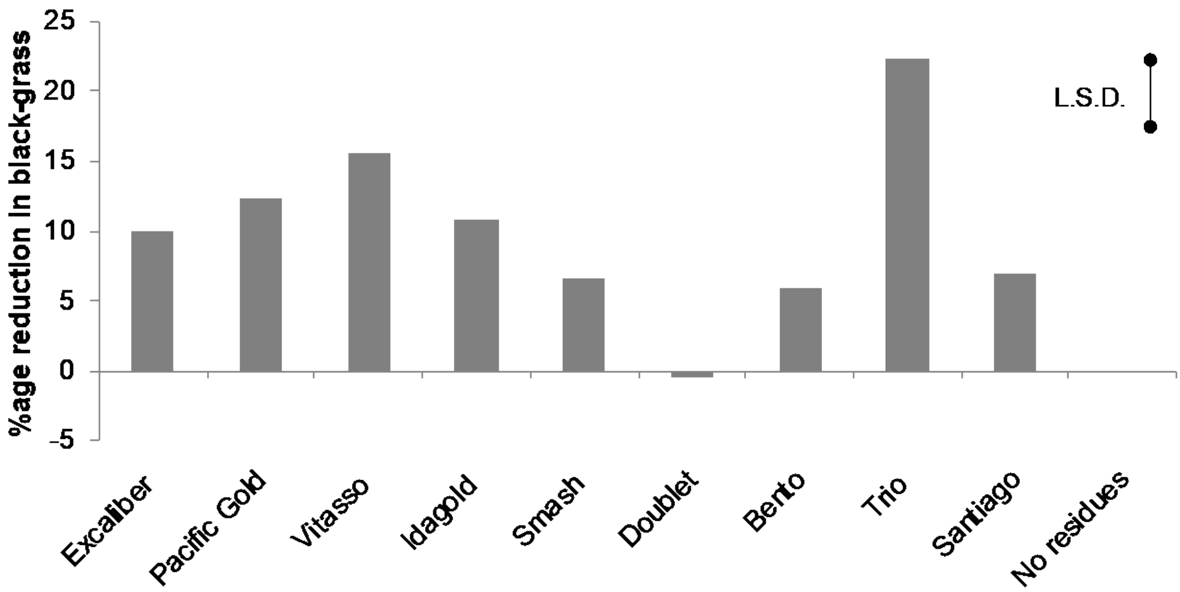

Figure 27 Percentage reduction in black-grass foliage over 8 weeks growth compared with the un-amended control after incorporation of residues to evaluate the potential for biofumigant reside to reduce black-grass early growth. Pot experiment 2012/13. Treatment details given in Table 2. Least significant difference is 12%.

Germination of black-grass seed was reduced in the presence of the residue extracts with a small but significant decrease where wheat residue extract was added and a greater reduction for many of the extracts taken from brassica species (Figure 28).

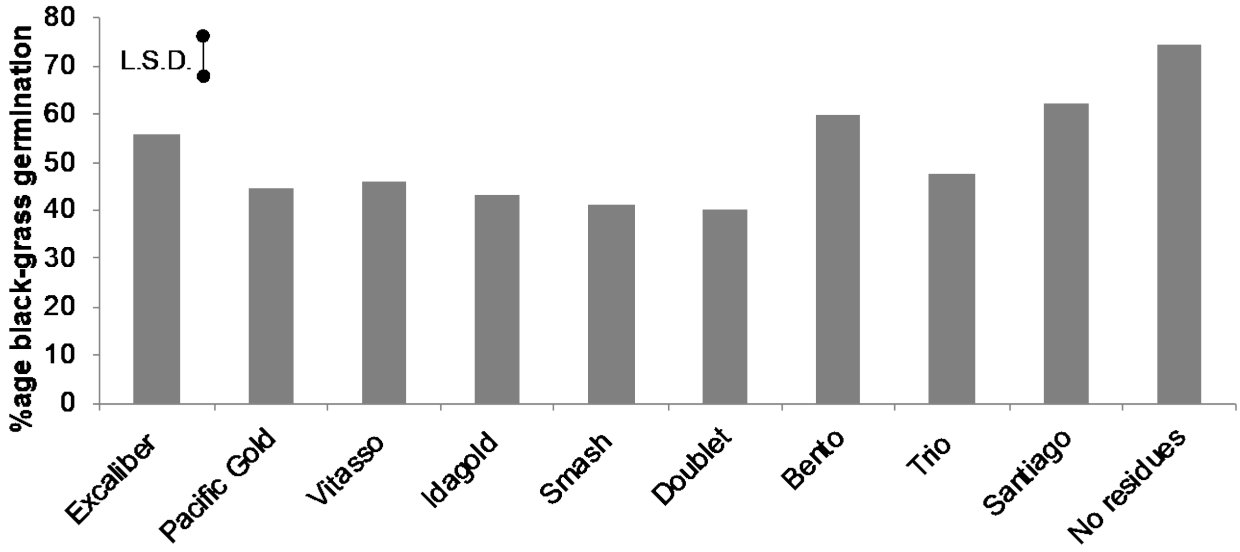

Figure 28 Percentage germination of black-grass seed achieved in a petri-dish germination test 2012 using extracts from the biofumigant residues. Treatment details given in Table 2. Least significant difference is 12%.

4.4.2. Effects of biofumigant mustard (Vitasso) residues on weed and crop species

The effect of the presence of the biofumigant mustard residue on the crop and weed species was variable within and between trials in the glasshouse studies (Figure 29). There were no consistent biofumigant effect of the mustard residue across all species. There were no significant differences to the un-amended control in trial 1; in trial 2 there were some significant species specific effects seen with the largest reduction in early black-grass growth.

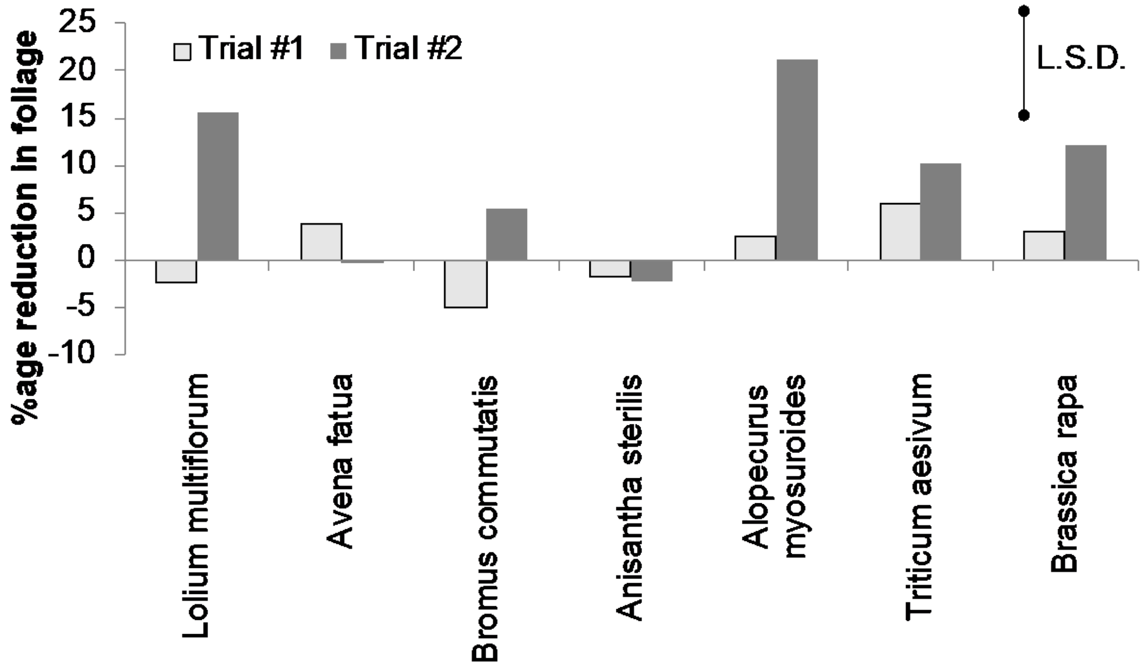

Figure 29 Percentage reduction in early-growth foliage of weed / crop species over 8 weeks compared with the un-amended control after incorporation of biofumigant mustard (Vitasso) residues to evaluate the potential for weed biocontrol. 4 replicates of each treatment in two separate replicate pot experiments 2013/14. Least significant difference is 12%.

5. Discussion

Cover crops have been suggested as a tool to enhance weed management by:

1) preventing germination/ establishment and/or smothering weeds during the growth of the cover crop;
2) mowing of long-term/perennial covers effectively controls annual weeds promoting further suppression by the perennial cover crop, and;
3) germination of weeds in the following crop may be inhibited by incorporating the cover crop residue (so called ‘biofumigation’).

We have not examined the first mechanism in any detail in this project, as these effects in the cover crop are not strongly relevant to the long-term success of the approach for black-grass control on a rotational basis. In this project the cover crop is fundamentally a trap-crop; the pest is encouraged to establish and thrive and, before the pest can reproduce, both the pest and the cover-crop are destroyed together. The grass weed population is reduced over the long-term by a combination of seeds being removed from the seed-bank by germination and establishment in the cover crop and the natural process of seed death in the soil. The eventual size of the grass weeds within the cover crop is not relevant to the long-term benefit, since an essential part of the approach is to destroy the crop before any seeds can be produced. In addition, any effect of the cover-crop that directly reduces the number of black-grass seeds that germinate may be counter-productive in the long-term since any reduction leaves a higher number of seeds in the seed-bank to carry over to the following crops. In fact, the stimulation of black-grass germination relative to a fallow treatment may be of more importance, so long as the black-grass can be controlled effectively before seed is set.

The project used pot trials to examine the extent and potential role of biofumigation and tested a biofumigant mustard in the field experiments established in autumn 2012 and 2013 (Section 4.1). A small, but variable, direct effect of biofumigation (or at least a reduction in seed germination and subsequent weed growth) was seen in the presence of actively decomposing residues. However, in practice the optimum conditions for bio-fumigant (no glyphosate and good soil mixing) are not ideal for field-scale weed management. In the field, there was no clear evidence of an additional black-grass control effect following a biofumigant mustard (Vitasso) compared with a conventional mustard or other cover crops in any of the field trials (Section 4.1). We have found no value for weed control of the use of biofumigant cover crops. However, it is important to note that biofumigant cover crops have been largely developed as tools for managing pests, especially nematodes, and they continue to have a role in integrated pest management strategies e.g. for beet cyst nematode (*Heterodera schachtii,* Hauer et al. 2016), potato cyst nematode (*Globodera pallida, G rostochiensis*) in potatoes (Ngala et al. 2015) and rhizoctonia root rot in sugar beet (Motisi et al. 2013).

The main focus of the project was to examine the role that cover crops play indirectly in a rotation to facilitate an underlying cultural control approach i.e. spring cropping or annual fallowing, rather than solely to examine the direct effects. Consequently the field trials compared the underlying cultural control approach (both spring cropping and annual fallowing) with the effectiveness of the same approaches in which a range of cover-crops were also adopted. This was combined with a modelling approach to try and draw out the general principles and to untangle the inter-locking mechanisms so that agronomy and management guidelines could be developed if such cover cropping had an important role in integrated weed management.

Modelling shows that where herbicide efficacy and crop competition are good, winter cropping can reduce the black-grass seed-burden effectively. Selective herbicides can not now be relied on to provide any thing like the >95% control needed to prevent black-grass populations increasing and a range of integrated approaches are needed (Moss et al. 2016). The modelling here shows that a slight reduction in herbicide efficacy (< 95%) or crop competition (< 300 plants m^{-2}) leads to a rapid worsening of the risk of increasing black-grass populations. In the trials at both sites, there were seasons where black-grass was very ineffectively controlled in the winter crops and also seasons where weed control was almost completely effective. Herbicide resistance, timing of application relative to emergence and soil moisture have been shown to markedly affect herbicide performance (Kudsk 2002).

Modelling shows that moving to an over-winter fallow followed by a spring crop has a large positive effect on the suppression of the weed seedbank. In trials at both sites, black-grass head numbers in spring cereals were usually significantly lower than, and never higher, than those measured in winter cropping. It is the change in the timing of crop establishment that had by far the largest effect – there were no clear additive differences seen that resulted from an overwinter cover crop. The modelling predicts that any reduction in weed emergence in over-winter stubbles through the establishment of a cover crop has a small net negative impact on weed control. Seed return in the spring crop can also be minimised by ensuring that the soil is disturbed as little as possible during drilling, hence an overwinter cover crop has the potential to improve soil conditioning and facilitate direct drilling in the spring. However, the timing and method of cover crop destruction has been shown to affect soil temperature, soil moisture, nutrient cycling, tillage and drilling operations of the following crop and potential impact of allelopathic compounds on the following crop establishment. White et al. (2016) highlight the need for more detailed understanding to allow decisions about when and how to destroy the cover crop to be optimised and to be site and situation specific (Balkcom et al. 2012). Over-winter cover cropping can improve soil health and provide some benefits for biodiviersity, but because of the short-duration of the crops, these are limited (White et al. 2016).

Where a field is to be taken out of production for a whole 12 months, then excellent black-grass control was shown where a spring cover crop was established after an overwinter bare fallow with multiple cultivations. Long-duration cover crops are an important tool to increase arable vegetation diversity for the portion of the season, the potential benefits to biodiversity are enhanced where the cover crop duration is increased (Tschumi et al. 2016). Spring sowing also increases the range of cover cropping options available and may allow a cover cropping mix designed for pollinators to be established more effectively. The costs to the farming system of taking a field (or part of a field) out of production for a season are significant. This work shows no added value for weed control of establishing cover crops in that break, hence the on-farm decision on the management (and its cost) of an extended fallow will focus, as currently, on the potential future cost of not effectively managing a problem weed population compared with the lost income from a cash crop in one season.

Other agronomic factors have much more significant effects on the population dynamics of black-grass: cultivations and the timing of cultivations, use and timing of glyphosate outside of the crop, the date of crop establishment and the diversity of rotation are all very significant drivers of grass weed population dynamics (Moss et al. 2016). Many of these agronomic variables are modified when cover crops are introduced and their effects can be confused or confounded with the direct effects of cover crops. Here we conclude that the direct effects of cover crops on grass weeds are small – almost all the effect on black-grass populations in field trials could be explained by the underlying cultural control approach. Therefore, maximising the effectiveness of a cover crop strategy as part of a weed control strategy involves maximising the effectiveness of the underlying cultural control approach. Therefore whilst there are costs associated with the establishment and management of cover crops, these are not clearly linked to weed control benefits and should be evaluated in terms of the wider benefits of cover cropping at cropping system scale.

Despite the difficulty in establishing cover crops in many of the trials, we have shown that the effects of cover crops on cash crops remain demonstrable. Our work also confirms the common farmer difficulty during implementation of cover cropping of selecting the most appropriate mix and also developing an effective approach to establishment (White et al. 2016). The best advice at the moment, as the evidence base is developing, is to focus on the known benefits of cover-crops in terms of improving soil conditions and biodiversity benefits (White et al. 2016); following crops will be better established particularly on the heavier soils where black-grass thrives, the seed-beds of following crops will be improved, increased infiltration rates will lead to less problems with waterlogging. These effects of the cover-cropping strategy will all work towards improving grass weed management even in the absence of any pronounced direct effect of the cover crop on the weed while it is growing, through improving timeliness of field operations.

Therefore an integrated weed management strategy should focus on the selection and timing of cultivations, use and timing of glyphosate outside of the crop, the date of crop establishment and the diversity of rotation as described in detail by Moss et al. (2016). No specific distinct agronomy or management guidelines are therefore required for the use of cover cropping within integrated weed management strategies. Above all it is important to focus on the basics of black-grass cultural control (Moss et al. 2016). If the strategy is to exhaust the seed bank prior to planting a crop (whether that is a spring crop or an autumn drilled crop following a year-long fallow), don't use deep primary cultivation that will mix the soil profile and reduce the effectiveness of that strategy. If spring cropping is the underlying approach and grass weed population levels have become a real challenge, then it is essential to select a spring crop where the weed can be effectively managed. Effective use of non-selective weed control both to destroy the weeds before they can set seed and (if relevant) to remove any weed seedlings that are present before the crop is drilled is also essential.

The research trials and modelling project carried out as part of the project confirm that well-established cover crops can play an important part in the rotation and in terms of supporting crop yield. However, in relation to the management of grass weeds in arable rotations, we conclude that cover crops should be seen as having a neutral or slightly negative effect on grass weed population dynamics over the rotation. The potential negative effects can nonetheless be mitigated by careful management. This project therefore concludes that cover cropping should continue to be considered as a support to the sustainable production of crops. However, the role of cover crops in modifying the population dynamics of grass weeds should not be overstated.

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