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Sustaining winter cropping under threat from herbicide-resistant black-grass (*Alopecurus myosuroides*)

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CONTENTS

1. Abstract

Black-grass (*Alopecurus myosuroides*) is an increasing problem in UK arable cropping systems due to the dominance of autumn sown crops and the high frequency of herbicide resistance. More integrated weed control strategies are needed and the aim of this project was to better quantify the impact of three non-chemical methods for control of resistant black-grass: (1) time of autumn sowing of winter wheat; (2) impact of different crop seed rates; (3) impact of spring sown, in comparison with autumn sown wheat. These were investigated in a series of five field trials and associated modelling work both in the absence of herbicides and in combination with a robust herbicide programme involving both pre- and post-emergence herbicides typical of that used in wheat crops.

Delayed sowing of winter wheat by three weeks from mid/late-September to early/mid-October reduced black-grass infestations by **33%** on average. In addition, heads and seeds plant^{-1}, were reduced by an average of **49%**. **The most important finding was the better black-grass control achieved by the pre-emergence herbicides (240 g flufenacet ha^{-1} + 60 g diflufenican ha^{-1} plus 1600 g prosulfocarb ha^{-1}) when applied in later-sown crops.** This mean benefit, an additional **26%** control (above the 47% achieved at the first sowing date), was substantial. Most of these benefits came from delaying sowing by about three weeks to early-mid October, with relatively smaller additional benefits from delaying sowing until late October/early November.

Increasing seed rate helped suppress black-grass by up to **28%** However, it was clear that higher seed rates were less effective at reducing black-grass than delayed autumn sowing, which was a much more effective strategy overall due to a combination of reduced black-grass plant populations and better herbicide efficacy. Crops sown at low seed rates (175 seeds m^{-2}), or which established poorly, were more vulnerable to black-grass and it was concluded that avoiding low-density crops must be a key objective. Spring sown wheat appeared to be a good solution due to the substantial (**92%**) reduction in black-grass plants emerging compared with September-sown wheat and the lower seed production per plant. These factors more than compensated for the modest control (**55%**) achieved by pre-emergence herbicides (pendimethalin+prosulfocarb) in spring wheat.

These findings show that delayed autumn drilling and use of higher seed rates, in conjunction with a robust herbicide programme, can make a very useful contribution to reducing the threat from herbicide-resistant black-grass. However, these measures alone will not be sustainable in intensive arable rotations if resistance continues to increase, especially to the pre-emergence herbicides. The results also show that spring cropping has much potential but can be a difficult option, especially on the heavy soils which greatly favour black-grass. There are no easy options or ‘quick

fixes', but a return to more balanced rotations and a move away from ever-earlier drilling must be the longer-term goal – a reversal of the trends that have occurred over the last 40 years.

2. Introduction

Black-grass (*Alopecurus myosuroides*) is an increasing problem in UK arable cropping systems for four main reasons:

1. **Most black-grass seedlings emerge in autumn** – black-grass seeds have a relatively short period of innate dormancy, although this is affected by environmental conditions during seed maturation in June and July (Swain *et al*., 2006). Over 80% of black-grass seedling emergence occurs in late summer and autumn, from August to November (Figure 1).

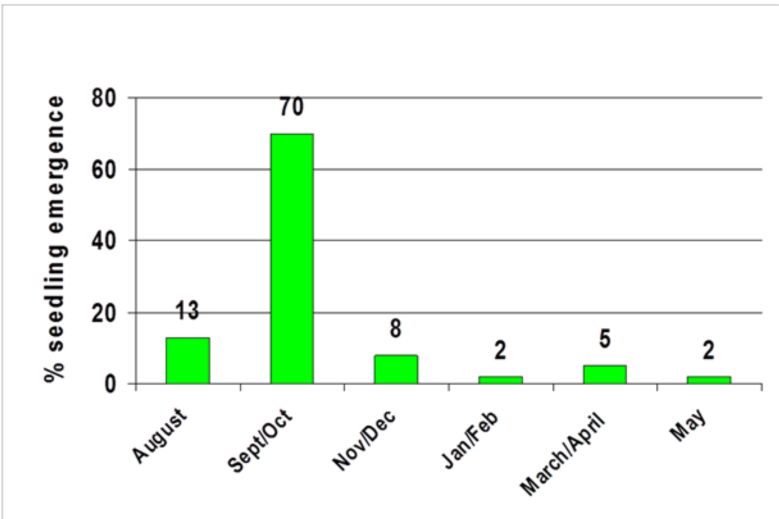

Figure 1. Black-grass seedling emergence – > 80% emerge in early autumn (Moss, 1980).

2. **Most arable crops are sown in autumn** – in 2014 about 70% of the total arable area of 4.7 million ha was planted with crops sown in autumn, principally winter cereals and oilseed rape (Figure 2).

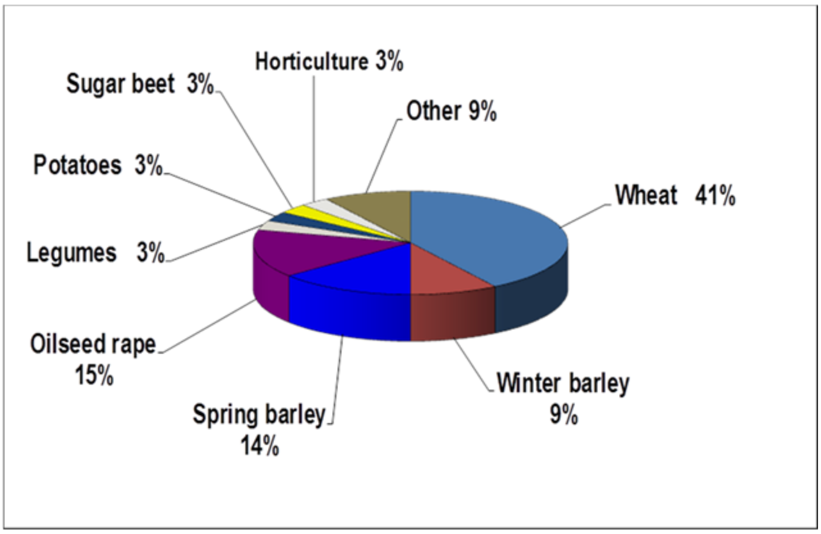

Figure 2. UK Arable Cropping 2014. (Total arable area, including horticulture = 4.7 million ha) (Defra, 2014).

3. **Autumn sown crops tend to be sown earlier than in the past**, coinciding with peak black-grass germination – the area of oilseed rape (mainly sown in August) has increased 18-fold and the proportion of winter wheat sown in September has increased 10-fold in the last 40 years, from about 5% to 50% of the total area sown (Figure 3).

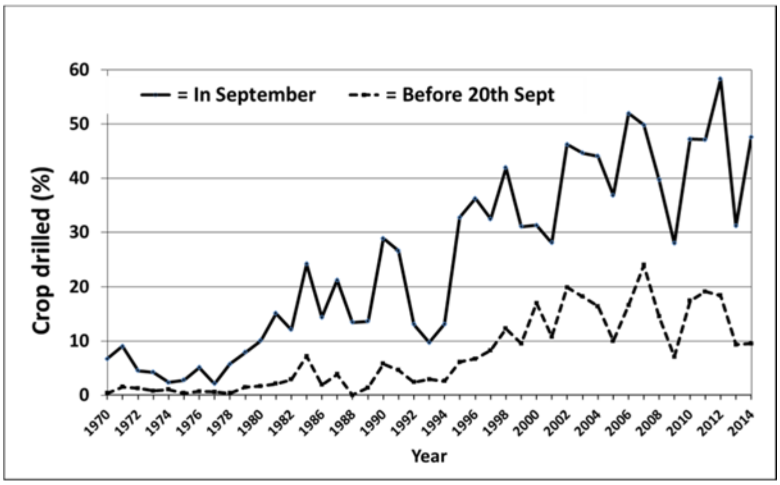

Figure 3. Proportion of winter wheat crops in England sown in September, and before 20th September in 1970 – 2014 harvest years (Crop Monitor, 2015).

4. **Herbicide resistance in black-grass is now very widespread** – by 2013 resistance occurred on virtually all of the estimated 20,000 farms in 35 counties where herbicides were applied regularly for its control (Figure 4). On most farms resistance is partial, rather than absolute, and reduced, rather than no efficacy, is more typical. The last major new herbicide for black-grass control was the formulated mixture of two sulfonylurea (ALS) herbicides, mesosulfuron-methyl + iodosulfuron-methyl-sodium, combined with the safener mefenpyr-diethyl, which was introduced into the UK market in autumn 2003 as 'Atlantis WG' (Bayer CropScience). Resistance to this herbicide was detected soon after its

introduction and, by 2013, resistance had been confirmed on >700 farms in 27 counties in England and continues to increase (Hull *et al*., 2014).

Figure 4. Counties (35) with herbicide-resistant *Alopecurus myosuroides* (black-grass) by 2013 (Hull *et al*., 2014).

The early-autumn seedling emergence characteristic of black-grass explains its success as a weed of autumn-sown arable crops. Although many factors, especially soil moisture, dormancy status and cultivations, will determine the precise periodicity of emergence in individual fields, it is clear that the earlier crops are sown in the autumn, the greater the proportion of total black-grass emergence that will occur within the crop, rather than pre-sowing when plants could be more easily destroyed (e.g. with cultivations or non-selective herbicides). This trend for more autumn cropping with ever-earlier sowing, as outlined above, would be of no consequence if selective herbicides could be relied on to give the high levels (>95%) of control required to prevent black-grass infestations increasing over a period of years (Moss *et al*., 2010). This is evidently not the case due to widespread occurrence of herbicide-resistance which is a direct consequence of farmers' over-reliance on chemical weed control since herbicide-resistant black-grass was first detected in the UK in 1982 (Moss & Cussans, 1985).

It is now clear that more integrated approaches are needed in which herbicide use is better integrated with non-chemical methods of control. These have recently been reviewed by Lutman *et al*., 2013) and a summary is presented in Table 1.

Table 1. Non-chemical methods of black-grass control in winter cereals, based on a review of over 50 field experiments (Lutman *et al*., 2013).

	% control of black-grass achieved		
Method	**Mean**	**Range**	**Comments**
Ploughing	**69%**	-82% to 96%	Rotational ploughing has considerable benefits

Delayed autumn drilling (by ≈ 3 weeks from mid Sept.)	**31%**	-71% to 97%	The later the better – but increased risk of poor conditions
Higher seed rates	**26%**	+7% to 63%	The higher the better – but lodging issues + cost implications
More competitive cultivars	**22%**	+ 8% to 45%	Useful, but marginal effects
Spring cropping	**88%**	+ 78% to 96%	Effective, but challenging on heavy soils and limited herbicides
Fallowing/grass leys	**70–80 %** per year (of seedbank)	–	Absence of new seeding critical

It is worth noting that in most of the trials reviewed, herbicides were *not* used so that the direct effect of the control method under study could be determined without the confounding effects of differential herbicide efficacy between treatments, which can complicate interpretation. This approach is not unreasonable but as 97.3% of the winter wheat area was treated with herbicide in 2014, could be considered unrealistic (Garthwaite *et al*, 2015).

The aim of this project was to better quantify the impact of three of these non-chemical methods which are of particular interest to farmers with resistant black-grass:

- impact of the time of autumn sowing of winter wheat on black-grass infestation
- impact of different seed rates on suppression of black-grass
- impact of spring-sown, in comparison with autumn-sown wheat

A key novel aspect of this project was to study these methods both in the absence of herbicides and in combination with a robust herbicide programme typical of that used in wheat crops. This programme specifically did not include mesosulfuron+iodosulfuron (‘Atlantis’) despite it being the most widely used post-emergence herbicide when these studies were initiated. The rationale for this was other research which showed that resistance was evolving rapidly (Hull *et al*., 2014; Moss *et al*., 2014) and that its long-term value as a post-emergence herbicide for black-grass control was questionable. This decision now appear well-founded, as the average control by mesosulfuron+iodosulfuron across Bayer trials conducted in 2014/15 was cited as being only 55%, with a range of 30 – 90% (Anderson-Taylor, 2015).

In addition, the data from the experiments was incorporated into an existing mechanistic model (Moss *et al*., 2010) with the aim of improving our ability to quantify the level of control still needed from herbicides, and whether this is realistic when used in combination with non-chemical control methods.

The outcomes of the project were aimed at providing practical crop management guidelines to better enable farmers to sustain predominantly winter cropping rotations in the presence of multiple-herbicide resistant black-grass.

3. Materials and methods

3.1. Field trial design and methodology

Five winter wheat field trials were conducted, three by Rothamsted Research in 2010-11, 2011-12 & 2012-13 and two by NIAB TAG in 2010-11 & 2012-13 at the following locations (Table 2). Plots of wheat sown in spring were also included in the three Rothamsted trials and one NIAB trial. Black-grass at all locations was partially resistant to most of the herbicides included in the resistance screens although some control was achieved (Table 2). The resistance status of all fields was similar to many others in England, and by no means atypical.

Table 2. Details of field trial site locations and resistance status of black-grass.

		Resistance status of black-grass – % reductions and R ratings*				
Code used	Location	clodinafop 30g ha^{-1}	meso+iodo. 12+2.4 g ha^{-1}	chlorotoluron 2.75 kg ha^{-1}	cycloxydim 150 g ha^{-1}	pendimethalin 5 ppm
Roth 10/11	Broadmead field, Woburn Beds.	47% **RR**	74% **RR**	89% **S**	42% **RR**	–
NIAB 10/11	Ketteringham, Norfolk	24% **RRR**	97% **S**	56% **RR**	20% **RRR**	65% **RR**
Roth 11/12	Warren field, Woburn, Beds.	29% **RRR**	63% **RR**	76% **RR**	29% **RR**	82% **R?**
Roth 12/13	Warren field, Woburn, Beds.	–	0% **RRR**	58% **RR**	21% **RRR**	59% **RR**
NIAB 12/13	Hardwick, Cambs	–	9% **RRR**	56% **RR**	36% **RRR**	–

* = % reductions in foliage weight or reductions in seedling growth in glasshouse pot or Petri-dish (pendimethalin) assays and 'R' resistance ratings (Moss *et al*, 2007), based on seed samples collected in June from each field prior to the start of each experiment. Note that control of a susceptible standard (Broadbalk) included in all assays was 92% – 100%.

The soil at the three Rothamsted Research (Roth) sites was a heavy clay loam, a clay loam at NIAB 10/11 and a heavy clay loam at NIAB 12/13. The previous crops were wheat at Roth 10/11, Roth 12/13 and winter beans at Roth 11/12. At NIAB sites they were winter beans (2010/11) and winter oilseed rape (2012/13). The trials were conducted to the following protocol:

Cultivations: Trial areas were cultivated to 20 cm after the previous harvest with tine/disc cultivators and seedbeds prepared prior to each drilling date. A combination powered cultivator with drill attached (12.5 cm row width) was used to sow all experiments. Glyphosate was applied prior to each drilling date to ensure no black-grass that had emerged prior to drilling survived.

Main plot size: 6 m wide (therefore each sub plot was 3 m wide) and 12 m long.

Experimental design: 3 replicates of 3 drilling dates x 3 seed rates = 9 main plots/rep. Each main plot was split randomly into two sub-plots (3 x 12 m) with one treated with herbicide and the other left untreated, although all other treatments were identical. Thus there were 27 main plots per trial and 54 sub plots in total. In the trials with spring sown wheat, one additional main plot was added to the design, again with two sub-plots. Each trial comprised a fully randomised block design.

Winter wheat variety: Oakley (all Roth experiments); Claire (2010/11 NIAB) and KWS Santiago (2012/13 NIAB).
Spring wheat variety: Paragon (all Roth experiments); Mulika (NIAB).

Target drilling dates: Mid-September, early October, late October, with the aim of drilling dates being, ideally, 2–3 weeks apart for winter wheat. Mid-March for spring wheat.

Seed rates: Three winter wheat seed rates of 175, 350 & 525 seeds m^{-2} giving target crop densities of 125, 250 & 375 plants m^{-2} assuming 71% emergence. These seeds rates are typical of the range currently used in the UK. In unfavourable conditions, seed rates were increased at later drilling dates. Spring wheat – 350 seeds m^{-2}.

Herbicide programme: a pre-emergence followed by an early post-emergence treatment.
Pre-emergence*: Flufenacet** (240 g a.i. ha^{-1}) + **diflufenican** (60 g a.i. ha^{-1}) (= ‘Liberator’ @ 0.6 l ha^{-1}) ***plus **prosulfocarb** (1600 g a.i. ha^{-1}) (= ‘Defy’ at 2 l ha^{-1}), applied within 7 days of drilling on respective treated sub-plots.
Early post-em*: Clodinafop** (30 g a.i. ha^{-1}) + **prosulfocarb** (2400 g a.i. ha^{-1}) (= ‘Auxiliary’ @ 3 l ha^{-1}) ***plus **flufenacet** (120 g a.i. ha^{-1}) + **pendimethalin** (600 g a.i. ha^{-1}) (= ‘Crystal’ @ 2 l ha^{-1}), applied at the1–2 leaf stage of black-grass on respective treated sub-plots. ‘Toil’ methylated rapeseed oil @ 0.5% spray volume used as adjuvant with ‘Auxiliary’. All herbicides applied at a water volume of 200 L ha^{-1} at 210 kPa using a hand-held plot sprayer fitted with flat fan nozzles.

Spring wheat pre-emergence only*: Prosulfocarb** (2400 g a.i. ha^{-1}) (= ‘Defy’ @ 3 l ha^{-1}) ***plus **pendimethalin** (800 g a.i. ha^{-1}) (= ‘Stomp 400 SC’ @ 2 l ha^{-1}).

All sub-plots, including those not treated with the black-grass herbicides above, received a standard fungicide programme and broad leaved weeds were controlled in spring using a herbicide having no activity on black-grass (fluroxypyr+florasulam, 'Starane XL' or metsulfuron+tribenuron, 'Ally Max'). After final assessments, all plots were destroyed by spraying glyphosate to prevent black-grass seed return, so no crop yields were recorded except at NIAB in 2012/13.

3.2. Plant and head assessments

Wheat establishment counts: determined about 4 weeks after drilling at the 2 leaf stage of the crop by counting wheat plants in 8 x 1m lengths per sub plot.

Black-grass pre-drilling plant counts prior to each of the drilling dates: Assessed before glyphosate and seedbed cultivations carried out so that the total emergence pre-sowing could be compared to that emerging within the crop. Every untreated sub-plot for that specific drilling date was assessed (9 sub-plots assessed prior to each drilling date) by counting black-grass in 10 x $0.1m^2$ random quadrats per sub plot.

Black-grass plant counts in the crop *prior* to early post-emergence herbicide application: Counts (in 10 x $0.1m^2$ random quadrats per sub plot) were made on both treated and untreated sub-plots immediately before post-emergence herbicide applications so that the efficacy of the pre-emergence treatments could be determined as well as quantifying black-grass emergence in relation to drilling date.

Black-grass plant counts in the spring: Counts (in 10 x $0.1m^2$ random quadrats per sub plot) were made on every sub-plot in February/March (April/May for spring sown wheat) so that the overall efficacy of the herbicide programme could be determined.

Black-grass head counts: Heads numbers were assessed in late May/early June in 10 x $0.1m^2$ random quadrats per sub plot.

Black-grass seed production: 15 heads per sub-plot were collected at random in early June, prior to seed shedding. Head length (mm) (on all 15 heads) and seeds per head (on a sub-set of 10 heads) were determined. Combining this information with the records for heads m^{-2} enable an estimate to be made of total seed production.

3.3. Monitoring individual black-grass plants

More precise information on black-grass emergence patterns and seed production was obtained by placing two 0.1 m^2 fixed quadrats on all untreated sub-plots of the three Rothamsted experiments

at the end of November. These were placed at either end of the plot (27 untreated sub-plots, 54 quadrats in total) and located with fixed pegs so the exactly the same areas could be reassessed.
End of November: Black-grass plants were counted and then removed with minimal disturbance from all fixed quadrats. The location of two autumn germinated black-grass plants close to, but **just outside,** each fixed quadrat was marked with plastic labels and all black-grass plants within 15 cm of the marked plants were removed to reduce intra-specific competition. These are **autumn emergers**.
End of February: Black-grass plants emerging since November were counted in each quadrat and then all **except two** plants were removed with minimal disturbance. These are **winter emergers**. These plants were labelled and the growth stage of both autumn and winter emergers recorded.
End of April: Black-grass plants emerging since February were counted in each quadrat and then all **except two** plants were removed with minimal disturbance. These are **spring emergers**. These plants were labelled and the growth stage of autumn, winter and spring emergers recorded.
June: Marked plants were removed and each plant assessed for heads per plant and seeds per head so that total seed return per plant could be estimated.

Thus the aim was achieve 108 labelled plants for each of the three germination periods giving a total of 324 marked plants. The rationale of this methodology was to eliminate the confounding effects of different weed population sizes associated with different sowing dates which would potentially confer differential degrees of intra-specific competition. Thus the aim was to see how differences in both drilling date and seed rate affected black-grass growth and seed production in the absence of intra-specific competition.

3.4. Modelling using data derived from the field experiments

Various scenarios were incorporated into the existing mechanistic black-grass model, produced in 2010, which was updated as part of a LINK project (LK0965) on Integrated Management of Herbicide Resistance (Moss *et al*., 2010). The 2010 model included most of the parameters from the original 1990 model as shown in Table 3.

Table 3. Parameters used in the black-grass population model in winter wheat (Moss, 1990).

Factor	Value	Parameter used in model
Seed survival in soil	30% annual survival	0.3
Seedling emergence from seeds in surface 5 cm soil	15% of new seeds 30% of old seeds	0.15 0.3
Herbicide efficacy	0 – 100%	0 to 1
Heads per plant	See below	See below
Seeds per head	100	100
Viability of seeds	55%	0.55
Survival of seeds on stubble	45%	0.45

Movement of seeds in the soil by ploughing	95% seeds within surface 5 cm are buried to over 5cm by ploughing; 35% of buried seeds are returned to the surface 5 cm layer by ploughing 25 cm deep.	Surface retention = 0.05 Burial = 0.95 Return to surface = 0.35 Depth retention = 0.65
Movement of seeds in the soil by tine/disc cultivations	100%, 80% and 60% of seeds within 5 cm of the soil surface are retained there by cultivations carried out to a depth of 5cm, 10cm or 20 cm respectively.	Very shallow tine or Direct drill = 1.0 10 cm tine/disc = 0.8 20 cm tine/disc = 0.6

The critical element of the original model that was updated in 2010, was the relationship between black-grass plant and head density as there was evidence that this had changed. The new relationship between black-grass plants and heads, based on data from 462 plots in 16 winter wheat experiments conducted between 1996 and 2008 was: **y = (B x) ÷ (1 + C x)**

where:

y = numbers of heads/m^2

x = number of plants/m^2

B = number of heads per plant under conditions of no intra-specific competition (8.71)

C = a constant governing the response rate to increasing plant density, calculated as B/the y axis asymptote (= maximum numbers of heads/ m^2 = 1517). C = 0.005741.

The 2010 revised model predicts that there are just over twice as many heads per plant at densities of up to about 25 black-grass plants m^{-2} compared with the original 1990 model, which used data collected in the 1970s and 1980s (7.7 – 8.7 v 3.7 – 3.9). This increase was thought to be a consequence of earlier sowing of winter wheat, lower cereal seed rates and milder winters.

The field experiments conducted as part of the current project provide realistic data which allow scenarios to be modelled which have not previously been included. These included the effects of autumn sowing date, spring cropping, seed rate and different pre-emergence herbicide efficacies. Further details of the specific model parameters used are given in the Results section.

4. Results

4.1. Wheat sowing dates and timings of pre and post emergence herbicides

The three target autumn sowing dates for winter wheat were achieved at all five sites over the three years: the first date being 16 – 21 September; the second being 3 – 11 October; and the third being 21 October – 5 November (Table 4). However, at the NIAB 10/11 site the crop sown on 5 November failed to establish due to wet conditions so no weed assessments were made. Spring wheat was sown between 15 March and 7 April.

Table 4. Wheat sowing dates and herbicide timings.

	Winter wheat			Spring wheat
Sowing date (target date)	**Date 1** (mid/late Sept)	**Date 2** (early/mid-Oct)	**Date 3** (late Oct/Nov)	Spring (mid-March)
ROTH 10/11	**16 September** Pre - 17 Sept Post - 18 Nov	**7 October** Pre - 12 Oct Post - 15 Dec	**5 November** Pre - 18 Nov Post - 8 Feb	**17 March** Pre - 20 March
NIAB 10/11	**16 September** Pre - 17 Sept Post - 14 Oct	**11 October** Pre - 14 Oct Post - 5 Nov	(5 November) Crop failed	-
ROTH 11/12	**16 September** Pre - 19 Sept Post - 14 Oct	**3 October** Pre - 4 Oct Post - 14 Jan	**21 October** Pre - 25 Oct Post - 14 Jan	**15 March** Pre - 23 March
ROTH 12/13	**21 September** Pre - 27 Sept Post - 14 Nov	**8 October** Pre - 19 Oct Post - 7 April	**27 October** Pre - 14 Nov Post - 7 April	**7 April** Pre - 1 May
NIAB 12/13	**20 September** Pre - 27 Sept Post - 30 Oct	**9 October** Pre - 10 Oct Post - 30 Oct	**30 October** Pre - 30 Oct Post - 23 April	**4 March** Pre - 5 March

4.2. Wheat plant establishment assessments.

The number of wheat plants for each treatment is shown in Table 5, averaged over treated and untreated plots as herbicide treatment had no significant effect on wheat establishment in any trial.

Table 5. Winter wheat plant establishment counts m^{-2}.

Sowing date (target date)	**Date 1** (mid/late Sept)			**Date 2** (early/mid Oct)			**Date 3** (late Oct/Nov)			
Seed rate m^{-2}	**175**	**350**	**525**	**175**	**350**	**525**	**175**	**350**	**525**	**S.E.±**
Roth 10/11	121	225	342	139	230	317	106	230	312	10.6
NIAB 10/11	117	211	300	88	186	275	-	-	-	12.0
Roth 11/12	121	217	330	103	206	285	121	216	306	13.5
Roth 12/13	81	147	256	14	35	114	15	45	75	22.1
NIAB 12/13	147	156	199	125	150	177	101	103	159	9.62
Mean	117	191	285	94	161	234	86	149	213	
% emergence	67%	55%	54%	54%	46%	44%	49%	42%	41%	

Spring wheat = 151, 154, 121 plants m^{-2} (mean 41% establishment) for the three Rothamsted experiments.

The higher the seed rate, the higher the resulting wheat population, with the overall % establishment averaging 57%, 48% and 46%, respectively, for the three autumn sowing dates. The

% establishment varied considerably between experiments and was generally lower than planned averaging only 50%. This was largely a reflection of the wheat populations in both 2012/13 trials which were much lower than planned, especially at the second and third sowing dates. This was a consequence of very wet autumn conditions which made sowing a challenge on many farms in England and affected wheat establishment. October and November 2012 rainfall totalled 115.8 and 100.4 mm, respectively, at Rothamsted, 34.1% and 23.8% above the 30 year (1981–2010) mean, with rain (>0.2 mm) falling on 26 days in October.

4.3. Black-grass plant counts pre-drilling

The numbers of black-grass plants that emerged prior to each sowing date are shown in Table 6. After assessment, these plants were destroyed with a treatment of glyphosate and seedbed cultivations prior to sowing the wheat crop to ensure that none were transplanted and re-emerged within the subsequent crop.

Table 6. Black-grass plant counts m^{-2} pre-sowing.

	Winter wheat			Spring wheat
Sowing date (target date)	**Date 1** (mid/late Sept)	**Date 2** (early/mid Oct)	**Date 3** (late Oct/Nov)	Spring (mid-March)
ROTH 10/11	0	56	637	651
NIAB 10/11	0	470	595	-
ROTH 11/12	0	159	156	263
ROTH 12/13	0	4	63	57
NIAB 12/13	-	-	-	-

As expected, there was a tendency for more plants to emerge prior to the later sowing dates. However, few additional plants emerged after late October as the numbers present prior to sowing spring wheat were similar to the numbers present prior to the third autumn sowing date. Successful seedling emergence is only one means of seed loss as germination, but unsuccessful emergence, may occur from deeply buried seeds and many seeds may simply decay or be eaten by a range of macro- and micro-organisms. Other seeds will remain dormant in the soil, even for several years. Thus, there is unlikely to be a simple relationship linking sowing date with the numbers of black-grass plants emerging pre- and post-sowing.

4.4. Black-grass plant assessments in the wheat crops

As expected, the numbers of black-grass plants emerging in the crop was little affected by the wheat seed rate used, showing that there is no evidence that the presence of germinating wheat affects black-grass germination (no allelopathic effect of wheat on black-grass, at least on germination and seedling emergence). Table 7 shows the black-grass populations averaged over drilling date and herbicide treatment (herbicide/untreated).

Table 7. Black-grass plants m^{-2} averaged over drilling date and +/- herbicide treatment.

Wheat seed rate m^{-2}	175	350	525	F pr.
Roth 10/11	237	350	295	0.571 n.s.
NIAB 10/11	183	161	161	0.133 n.s.
Roth 11/12	177	142	119	0.033 sig.
Roth 12/13	30	29	33	0.962 n.s.
NIAB 12/13	24	20	26	0.063 n.s.
Mean	130	140	127	n.s. = non sig

On only one trial was there a statistically significant (*P≤0.05*) difference between wheat seed rates and those differences were relatively small. Consequently, the data for black-grass plant populations, as affected by sowing date and herbicide treatment, was averaged over all three seed rates (Table 8).

Table 8. Black-grass plants m^{-2} on untreated (Nil) & treated (Herb) sub-plots after receiving the full herbicide programme (pre- + post-emergence treatments) (averaged over wheat seed rates).

		Winter wheat					
Sowing date:		**Date 1** (mid/late Sept)	**Date 2** (early/mid Oct)		**Date 3** (late Oct/Nov)		Spring wheat
Site		Black-grass plants m^{-2}	Black-grass plants m^{-2}	% red. to Date 1	Black-grass Plants m^{-2}	% red. to Date 1	
Roth 10/11	Nil	649	141	**78**	67	**90**	25
	Herb	126	17		8		15
NIAB 10/11	Nil	708	418	**41**	**-**	**-**	**-**
	Herb	39	11		**-**	**-**	**-**
Roth 11/12	Nil	205	288	**- 41**	238	**- 16**	26
	Herb	71	37		36		8
Roth 12/13	Nil	100	23	**77**	16	**84**	7
	Herb	10	3		1		2
NIAB 12/13	Nil	62	58	**8**	6	**90**	5
	Herb	7	5		3		1
Mean	Nil	345	186	**33%**	82	**62%**	11
	Herb	51	15		12		

The size of the black-grass populations varied considerably between sites, ranging from 62 to 708 plants m^{-2} in the untreated crops at the first sowing date. Averaged over all sites and in the absence of herbicide, delaying sowing resulted in a progressive reduction in the black-grass infestation of **33%** to the second and **62%** to the third sowing date. However, there was considerable variation between individual sites with an increase in infestation level with delayed sowing at the Roth 11/12 site. This was probably a reflection of the dry conditions that occurred that year that restricted germination especially at the first sowing date. September, October and November 2011 rainfall totalled 38.4, 25.2 and 36.4 mm, respectively, at Rothamsted, 19.2%, 56.5% and 40.2% below the 30 year (1981–2010) mean. These results show that while delayed autumn sowing can appreciably reduce the potential black-grass infestation directly, the scale of the reduction is likely to vary considerably between fields and weather conditions, especially soil moisture, will have a big influence.

Spring-sown wheat resulted in greatly reduced black-grass infestations, with a 96%, 87%, 93% and 92% (mean = 92%) reduction in plant population on untreated sub-plots for four sites (in order as listed in Table 8), relative to the populations in wheat sown at the first autumn sowing date.

The herbicide programme reduced black-grass plant populations, as would be expected (Table 8). There appeared to be at least an additive effect of delayed sowing and use of herbicides and substantial reductions in black-grass infestations were achieved. The mean population on untreated sub-plots at the first sowing date was 345 plants m^{-2} and a combination of delayed sowing and herbicide programme reduced this to a mean of 15 and 12 plants m^{-2} at the second and third drilling dates, respectively; a 96% and 97% reduction. However, there was variation between sites and any direct effect of delayed drilling on herbicide efficacy is rather difficult to observe from the plant population data alone.

4.5. Herbicide efficacy on black-grass plant assessments in the wheat crops

The novel design of the experiments, in which there was an untreated sub-plot alongside every treated sub-plot, meant that a much better assessment of herbicide efficacy could be made than where there are only one or two untreated plots per replicate, which is a more common design. The black-grass plant counts made in autumn on treated and untreated sub-plots, before post-emergence herbicides were applied, were used to calculate the efficacy of the pre-emergence herbicide applications. Subsequent spring assessments, after the additional effects of the post-emergence herbicides were evident, were used to determine the overall efficacy of the herbicide programme (pre- + post-emergence herbicides) (Table 9).

Table 9. Herbicide efficacy of both the pre-emergence applications and the full herbicide programme (pre + post-emergence treatments) as % reduction in black-grass plants m^{-2}, based on assessments made on untreated (Nil) & treated (Herb) paired sub-plots (averaged over wheat seed rates).

	Winter wheat							
Sowing date:	**Date 1** (mid/late Sept)		**Date 2** (early/mid Oct)		**Date 3** (late Oct/Nov)		**S.E.±**	
Herbicide treatment	Pre	Pre+post	Pre	Pre+post	Pre	Pre+post	Pre	Pre+post
Roth 10/11	45	80	62	88	72	88	3.38	1.27
NIAB 10/11	74	94	79	97	*	*	3.16	1.00
Roth 11/12	-1	65	44	87	51	85	10.38	2.38
Roth 12/13	57	89	97	83	88	88	4.67	10.38
NIAB 12/13	61	88	81	92	67	44	3.99	11.58
Mean	**47**	**83**	**73**	**89**	**69**	**76**	*	*

Spring wheat: % control of black-grass plants by herbicides at four sites = 23, 60, 52 & 86% control (using individual rep data). Mean = 55%.

Pre-emergence herbicides gave significantly ($P \leq 0.05$) better control of black-grass when applied at later sowing dates at four of the five sites. The mean control at the second sowing date (**73%**) was **26%** greater than the control achieved (**47%**) with the same pre-emergence herbicides applied at the first sowing date. This represents a very substantial benefit from delaying sowing by an average of about 3 weeks. Compared with the second sowing date, there was no additional benefit in terms of better control from pre-emergence herbicide efficacy at the third sowing date, although there was data for only four sites. Not surprisingly, the scale of the increase in efficacy varied between sites, although it was significant that a benefit was achieved at ***all*** sites, indicating that this was a consistent effect.

The greatest benefit (45%) occurred at the Roth 11/12 site where no control by pre-emergence herbicides was achieved at the first sowing date. This was also the only site where black-grass populations increased with later sowing dates (Table 8). These effects on weed infestation and pre-emergence herbicide efficacy are almost certainly a reflection of the dry conditions that occurred that year, as explained in section 4.4 above. However, despite delayed drilling resulting in an increase in black-grass infestation on untreated sub-plots, the better efficacy of pre-emergence herbicides at the later sowing dates more than compensated, resulting in a clear benefit to delayed sowing even at this site.

The control of black-grass plants achieved by the full herbicide programme (pre + post-emergence treatments) averaged **83%** (range = 44% – 97%) over all sites and sowing dates. Over 80% control was achieved on 12 of the 14 site x sowing date comparisons. Note that this refers specifically to herbicide efficacy and does not account for the generally lower black-grass infestations at later sowing dates. By calculating the % reductions in black-grass plant populations relative to those on untreated sub-plots at the first sowing date, it was shown that a combination of delayed sowing and full herbicide programme achieved a 93% to 94% reduction in black-grass plant populations at the second and third sowing dates, respectively (based on means of calculations for each individual site, not overall means). This compares with the mean 83% control achieved by the herbicide programme at the first sowing date.

The pre-emergence herbicides used in spring wheat crops gave variable (23 – 86%) and mainly modest levels of control, averaging **55%**. Such variable control is not unexpected, as similar variability occurred with autumn applications. However, the fact that black-grass populations were greatly reduced in spring-sown wheat, even in the absence of herbicides, meant that the combination of spring-sown wheat and a pre-emergence herbicide resulted in relatively low surviving black-grass plant populations (1 – 15 plants m^{-2}).

4.6. Black-grass head assessments in the wheat crops

Differences in crop population as a consequence of different seed rates are likely to affect the degree of inter-specific competition between wheat and black-grass. This is likely to affect the tillering capacity, and hence number of heads, produced by each black-grass plant. On untreated plots, with high black-grass infestations, intra-specific competition is likely to play a larger role in determining black-grass head populations and consequently the effect of different crop seed rates is likely to be less evident. As herbicides are used routinely for controlling black-grass it seemed appropriate to focus mainly on the effects of different crop seed rates on the herbicide-treated sub-plots, as this is likely to be most relevant in practice. However, a summary of the head densities on both treated and untreated plots is given in Table 10, averaged over crop seed rates.

The mean % reduction in black-grass head densities on untreated sub-plots as a consequence of delayed sowing (45% & 62% – Table 10) are broadly similar to those recorded for plant densities (33% & 62% – in Table 8). The herbicide programme gave better control of black-grass heads with later sowing dates, increasing from 53% at the first date to 81 – 82% at the later sowing dates. Note that, as with the plant assessments data, the figures refer specifically to herbicide efficacy and do not take account of the additional benefit of the generally lower black-grass head infestations at later sowing dates.

Table 10. Black-grass heads m^{-2} on untreated (Nil) & treated (Herb) sub-plots after receiving the full herbicide programme (pre + post-emergence treatments) (averaged over wheat seed rates). Figures in brackets are the % control achieved by the herbicide programme.

		Winter wheat				
Sowing date		**Date 1** (mid/late Sept)	**Date 2** (early/mid-Oct)		**Date 3** (late Oct/Nov)	
Site		Black-grass heads m^{-2}	Black-grass heads m^{-2}	% red. to Date 1	Black-grass heads m^{-2}	% red. to Date 1
Roth 10/11	Nil	1386	427	**69**	185	**87**
	Herb	752 **(46%)**	52 **(88%)**		8 **(96%)**	
NIAB 10/11	Nil	795	198	**75**	–	–
	Herb	342 **(57%)**	24 **(88%)**		–	–
Roth 11/12	Nil	708	742	**- 5**	740	**- 5**
	Herb	503 **(39%)**	329 **(56%)**		290 **(62%)**	
Roth 12/13	Nil	693	265	**62**	106	**85**
	Herb	183 **(74%)**	47 **(82%)**		5 **(95%)**	
NIAB 12/13	Nil	402	312	**22**	75	**81**
	Herb	205 **(49%)**	28 **(91%)**		19* **(75%)**	
Mean % reduction with later sowing	Nil	–	–	**45%**	–	**62%**
Mean % control from herbicides	Herb	**53%**	**81%**	**–**	**82%**	**–**

Spring wheat: black-grass heads m^{-2} (Nil/Herb) for four sites = 10.5/5.7; 47/16; 6/4.3; 1.3/0.1. Mean 48% reduction (using individual rep basis). * see note under Table 11.

The influence of crop seed rate on black-grass head densities on herbicide-treated sub-plots is shown in Table 11. There were large and significant (*P≤0.05*) differences between treatments, but it is clear that date of sowing and differences in herbicide efficacy had a much bigger influence on black-grass head densities than crop seed rate. Despite crop emergence being lower than planned, especially in 2012/13 (Table 5), there was still evidence that higher seed crop seed rates were beneficial in reducing black-grass head densities. Meaned over all sites and all three sowing dates, there were 220, 198 and 156 black-grass heads m^{-2} at the 175, 350 and 525 crop seed rates, respectively, corresponding to a **10%** reduction at the middle and a **29%** reduction at the highest seed rate compared with the lowest. These results support the recommendation to sow at high crop seed rates to help control black-grass by increasing crop competition. However, it is clear that higher seed rates should not be seen as an alternative to delayed autumn sowing, which was a much more effective strategy overall due to a combination of reduced black-grass plant populations and better herbicide efficacy.

Table 11. Influence of crop seed rate on black-grass heads m^{-2} on sub-plots receiving a full herbicide programme (pre + post-emergence treatments).

Sowing date	Date 1 (mid/late Sept)			Date 2 (early/mid Oct)			Date 3 (late Oct/Nov)			S.E.±
Seed rate m^{-2}	**175**	**350**	**525**	**175**	**350**	**525**	**175**	**350**	**525**	
Roth 10/11	754	786	717	70	57	28	10	9	5	62.3
NIAB 10/11	309	419	297	4	16	51	*	*	*	84.0
Roth 11/12	705	444	361	408	374	206	392	271	206	68.4
Roth 12/13	218	164	167	32	64	44	6	6	4	79.9
NIAB 12/13	211	221	183	33	38	12	34	16*	7	34.2
Mean	439	407	345	109	110	68	111	76	56	

* NIAB 12/13 date 3 medium seed rate value is based on two replicates as the other replicate produced an atypically high value (371 heads m^{-2}) as a consequence of lack of competition due to very poor crop establishment.

4.7. Black-grass seed production

A series of assessments was made to enable the influence of different treatments on black-grass seed production to be quantified. Seed production m^{-2} is a function of the number of black-grass plants m^{-2}, the number of heads per plant and the number of seeds per head.

4.7.1. Black-grass heads per plant

Seed production per plant is likely to be strongly influenced by the number of heads per plant. The number of black-grass heads per plant was calculated from the head and plant density data obtained for each sub-plot. A summary of the results is presented in Table 12 for treated sub-plots only, as these are more relevant to practical field conditions and should be less distorted by effects of intra-specific competition.

Table 12. Black-grass heads plant^{-1} as affected by crop sowing date on sub-plots receiving a full herbicide programme (pre + post-emergence treatments) (meaned over crop seed rate).

Sowing date	Date 1 (mid/late Sept)	Date 2 (early/mid Oct)	Date 3 (late Oct/Nov)	S.E.±
Roth 10/11	6.1	3.0	1.0	0.25
NIAB 10/11	10.0	1.6	-	1.21
Roth 11/12	8.1	9.3	8.6	0.87
Roth 12/13	32.2	13.8	8.8	4.13
NIAB 12/13	30.0	10.0	4.0	3.3
Mean	**17.3**	**7.5**	**5.6**	

Spring wheat: black-grass heads plant^{-1} (treated sub-plots) = 1.8, 1.9, 2.2, (0.2) mean = **2.0** (excluding value for NIAB 12/13 site due to very low population)

There was a distinct and significant (*P≤0.05*) trend for the number of black-grass heads per plant to decline with later sowing at four of the five sites, although no such trend was evident at ROTH 11/12. This atypical result may be a reflection of the very favourable growing conditions in summer 2012 which favoured tillering and head production in black-grass – while the control of plants was quite good (Table 9) the control in terms of head numbers was poor, especially at the two later sowing dates (Table 10), resulting a very high head densities even on treated sub-plots (Table 11). The mean reduction averaged **49%** and **59%** at the second and third sowing dates, respectively, based on calculations for each site, not overall mean. The number of black-grass heads per plant was substantially lower in spring-sown compared with autumn-sown wheat and this was consistent with the trend seen in autumn of fewer heads per plant, the later the sowing date.

4.7.2. Black-grass seeds per head

A very considerable amount of time was spent on collecting heads and assessing the numbers of seeds per head on black-grass samples from each sub-plot so that accurate estimates of seed return could be calculated and effects of sowing date, crop seed rate and herbicide treatment quantified. However, although the numbers of seeds per black-grass head varied between sites, there was remarkably little effect of crop sowing date, crop seed rate or herbicide treatment on the number of seeds per head.

Table 13. Black-grass seeds head^{-1} as affected by experiment site and crop sowing date (averaged over crop seed rate and +/- herbicide treatment).

Sowing date	**Date 1** (mid/late Sept)	**Date 2** (early/mid Oct)	**Date 3** (late Oct/Nov)	**S.E.±**
Roth 10/11	91	93	92	3.23
NIAB 10/11	107	120	-	5.08
Roth 11/12	111	129	129	3.79
Roth 12/13	150	132	124	4.65
NIAB 12/13	155	149	149	7.31
Mean	**123**	**125**	**124**	5.03

There were significant *(P≤0.05)* differences between sites in the number of black-grass seeds per head, with the lowest numbers at Roth 10/11 and the highest at NIAB 12/13, but sowing date had little effect (Table 13). Averaged over all sites, there was an average of **124** black-grass seeds per head.

Averaged over all sites, sowing dates and crop seed rates, there was an average of 117 and 115 (S.E. ± 2.91) black-grass seeds per head on untreated and herbicide treated sub-plots, respectively (excluding NIAB 12/13 for which data was only available for untreated sub-plots). Consequently there was no evidence that herbicide treatment affected the numbers of seeds per head.

There was a trend for black-grass seeds per head to decline as crop seed rate increased, and values were consistently lower at the highest compared with the lowest seed rate, averaged over herbicide treatment and sowing date. Averaged over all sites, sowing dates and herbicide treatments, there was an average of 127, 124 and 118 (S.E. ± 5.26) black-grass seeds per head for the low, medium and high crop seed rates, respectively. Consequently, differences in crop seed rate had relatively little effect on the numbers of black-grass seeds per head.

The numbers of black-grass seeds per head in the three Rothamsted spring wheat crops assessed, averaged over sites and herbicide treatments, were 62, 95 & 112 (mean = 90). This was 27% less than the mean numbers recorded in autumn-sown wheat crops.

4.7.3. Black-grass seeds production

All the information outlined above was used to calculate estimates of total seed return for all treatments (Table 14). These confirmed the very high potential seed production in black-grass, which averaged 87,959 seeds m^{-2} on untreated sub-plots at the first sowing date, averaged over sites and seed rates (range 62,292 – 119,553). Black-grass seed production in spring-sown wheat was much lower than in autumn-sown crops as a consequence of fewer plants, fewer heads per plant and fewer seeds per head.

In terms of quantifying the effects of sowing date, crop seed rate and herbicide efficacy, the very laborious procedure involved in measuring seed return offers virtually no benefit over the much simpler assessment of head numbers (Table 15). This is a consequence of the consistency of the value for mean seeds per head in black-grass plants, as detailed in the previous section. While this varies between sites to a limited degree, at any individual site it was little affected by sowing date, crop seed rate or herbicide treatment.

A mean 15.7% difference between assessments of black-grass control based on plant and head assessments is not unexpected, as individual black-grass plants will produce varying numbers of heads per plant as a consequence of inter- and intra-specific competition which is likely to vary between treatments (Table 15). In contrast there was only a 1.5% difference in calculations of overall herbicide performance made using black-grass head assessments compared with estimates of total seed return. Assessing the head densities on these field experiments took about one man-day per site. In contrast, the collection of hundreds of black-grass heads, together with counting seeds numbers and collation of the data, took at least one to two man-weeks per site for these experiments.

Table 14. Total black-grass seeds production m^{-2} as affected by experiment site, crop sowing date and +/- herbicide treatment (averaged over crop seed rate).

Sowing date	**Date 1** (mid/late Sept)		**Date 2** (early/mid Oct)		**Date 3** (late Oct/Nov)		**S.E.±**
Herbicide treatment	Nil	Herb	Nil	Herb	Nil	Herb	
Roth 10/11	119,553	71,538	41,274	4,740	18,933	683	2,970
NIAB 10/11	78,630	36,499	24,854	3,033	*	*	5,427
Roth 11/12	74,449	58,855	97,405	42,449	90,180	39,933	5,274
Roth 12/13	104,869	27,628	36,580	6,781	15,743	694	6,762
NIAB 12/13	62,292	31,640	46,464	4,056	12,113	2,486	4,994

Spring wheat: black-grass seeds production m^{-2} in the three Rothamsted experiments (Nil/Herb) = 674/344; 5015/1409; 676/484

Table 15. The % reductions in black-grass plant, head and total seed return due to herbicide treatment averaged over sowing dates and crop seed rates.

	Plants (from Table 9)	**Heads** (from Table 10)	**Seeds** (from Table 14)
Roth 10/11	85.3	76.5	75.0
NIAB 10/11	95.5	72.5	70.7
Roth 11/12	79.2	52.3	44.3
Roth 12/13	86.7	83.7	83.5
NIAB 12/13	74.2	54.3	73.3
Mean	**83.6 %**	**67.9 %**	**69.4 %**

Estimating seed return is clearly of value in population dynamics experiments where attempts are made to understand the processes underlying changes in weed populations over a period of years. For annual grass weeds such as black-grass, an accurate measure of seed viability would also be required, as this is always much less than 100%. This is an additional, laborious exercise as a consequence of the long shedding period of black-grass (Moss, 1983). Our experiments indicate that, with black-grass, an assessment of head density represents a very good measure for quantifying treatment effects, and also provides a good indicator of differences in seed return between treatments. This may well not be true for other weeds, where there may be much less consistency in the number of seeds per inflorescence.

4.8. Fixed quadrat assessments

The fixed quadrats were used primarily to assess black-grass seedling emergence patterns. The mean number of black-grass plants emerging in each of three assessment period is shown in Table 16.

Table 16. Black-grass emergence patterns (plants m^{-2}) in winter wheat in fixed quadrats on untreated sub-plots, averaged over sowing dates and crop seed rates.

Emergence dates:	**up to mid-Dec**	**between mid-Dec & early March**	**between early March & early May**	**S.E.±**
Roth 10/11	234	44	10	10.11
NIAB 10/11	-	-	-	-
Roth 11/12	264	13	6	12.17
Roth 12/13	65	9	1	6.71
NIAB 12/13	-	-	-	-
Mean	187	22	6	
% germination at emergence dates	**87**	**10**	**3**	*

On average, 87% of total black-grass seedling emergence occurred before mid-December and this was a consistent trend at all sites. There was no evidence for a 'spring flush' although a small proportion of plants did emerge in spring at all sites. In highly infested sites, the actual numbers of plants emerging in early spring could be significant, even when the proportions were low. This data confirmed that black-grass is predominantly an autumn-germinating weed species.

A second aim with the fixed quadrat assessments was to determine head and seed production per black-grass plant in the absence of the confounding effects of differences in intra-specific competition, which was a likely consequence of varying population sizes due to the different sowing dates. The method used, as detailed in the materials and methods, was less successful than anticipated. This was because the amount of worked involved meant that the planned sample sizes (12 marked plants per treatment) were marginal, and subsequent loss of plants meant that an inadequate number remained for a fair assessment of differences between crop seed rate. This was exacerbated by the differences in crop establishment between sites. However, pooling the data for the three crop seed rates improved the degree of replication and some useful data was obtained on the relationship between black-grass seedling emergence times and head and seed production.

Table 17. Black-grass heads per plant / seed production per plant for plants emerging during three periods in winter wheat in fixed quadrats on untreated sub-plots, averaged over sowing dates and crop seed rates.

Emergence dates	**Up to mid-Dec**	**Between mid-Dec & early March**	**Between early March & early May**	**S.E.±**
Roth 10/11	8.4 / 780	3.9 / 210	0.9 / 45	1.58 / 184.3
NIAB 10/11	–	–	–	–
Roth 11/12	8.8 / 1074	2.8 / 338	0.3 / 34	0.31 / 108.3
Roth 12/13	27.2 / 3310	28.2 / 3439	2.0 / 365	0.82 / 114.3
NIAB 12/13	–	–	–	–
Mean	**14.8 / 1721**	**11.6 / 1329**	**1.1 / 148**	
% reduct. in heads/plant at later emergence dates	**–**	**22%**	**93%**	**–**
% reduct. in seeds/plant at later emergence dates	**–**	**23%**	**91%**	**–**

There was a clear trend for head and seed production per plant to decline the later the black-grass plants emerged. This was especially striking for spring-emerging plants where there was a reduction of over 90% relative to autumn-emerging plants. It is important to recognise that this was in the absence of competition from other black-grass plants (no intra-specific competition) although there was competition from wheat plants (inter-specific competition). The atypical result for Roth 12/13, where there was little difference between the first two emergence periods was probably a consequence of the poor wheat establishment at that site which resulted in reduced inter-specific competition.

Although these results were from untreated sub-plots, they do mimic the situation where herbicides are used resulting in such a small number of survivors that little intra-specific competition occurs. This highlights the relative unimportance of spring-emerging black-grass in well-established winter wheat crops as, firstly, relatively few plants emerge in spring and, secondly, those that do, produce far fewer heads and seeds per plant than autumn emergers. The winter emergers were also less productive than autumn emergers, although the reduction in head and seed production per plant was far less than for spring emergers.

These results are entirely consistent with the heads per plant data presented in Section 4.7.1 for herbicide treated sub-plots. Both sets of data show clearly that delayed autumn sowing not only reduces black-grass plant populations directly, but also results in reduced head and seed production per plant from those plants emerging in later-sown crops.

4.9. The implications for crop yield

For the NIAB trial in 2012/13 (at Hardwick) there was an opportunity to continue the experiment and measure crop yields on all the plots. As a compromise plot combining was somewhat delayed (for a winter wheat crop) and took place on 28th August 2013. This was done so that the spring-sown plots had reached an appropriate level of grain maturity for harvest. Crop yield results are shown in Table 18; all the values for crop yield are expressed as $t.ha^{-1}$ at 15% moisture content.

Table 18. Crop yield ($t\ ha^{-1}$) for all combinations of sowing date, seed rate and herbicide treatment for the NIAB 2012/13 trial. In additional a value for the average % crop yield reduction observed on the untreated compared to equivalent herbicide treated plots is shown – this value is the average of the three seed rate treatments at each sowing date.

Sowing date	**Date 1** (20 Sept)			**Date 2** (9 Oct)			**Date 3** (30 Oct)			**Spring** (4 March)			**S.E.±**
Seed rate m^{-2}	**175**	**350**	**525**	**175**	**350**	**525**	**175**	**350**	**525**	**175**	**350**	**525**	
Treated	6.17	6.90	6.14	7.56	7.90	8.27	7.66	6.51	8.15	6.46	6.75	6.69	0.75
Untreated	3.26	4.60	3.67	4.35	4.58	4.94	7.45	5.34	7.95	6.37	6.58	6.87	
% age Yield reduction	**40.2**			**41.6**			**7.7**			**0.41**			

An analysis of variance for the crop yield data illustrates the over-riding influence of sowing date in this trial – where competition from black-grass was the key determinant of crop yield. The effect of sowing date was significant ($P<0.001$) but the effect of seed rate was not ($P=0.4$). The highest yield (8.27 $t\ ha^{-1}$) was achieved with the crop sown at the highest seed rate on 9 October and receiving a full herbicide programme.

This crop yield results for this trial reinforce the results for other measurements that were taken. The effect of sowing date on crop yield, largely through the impact of black-grass infestation, was dramatic. The crop yield reduction observed on the untreated plot-halves although relatively similar for the first two sowing dates (~40%) was dramatically reduced for the latest autumn drilling date (~8%) and for the spring wheat plots (~0.5%) – this finding reflects the effect of drilling date on both black-grass populations level and herbicide performance observed in these trials.

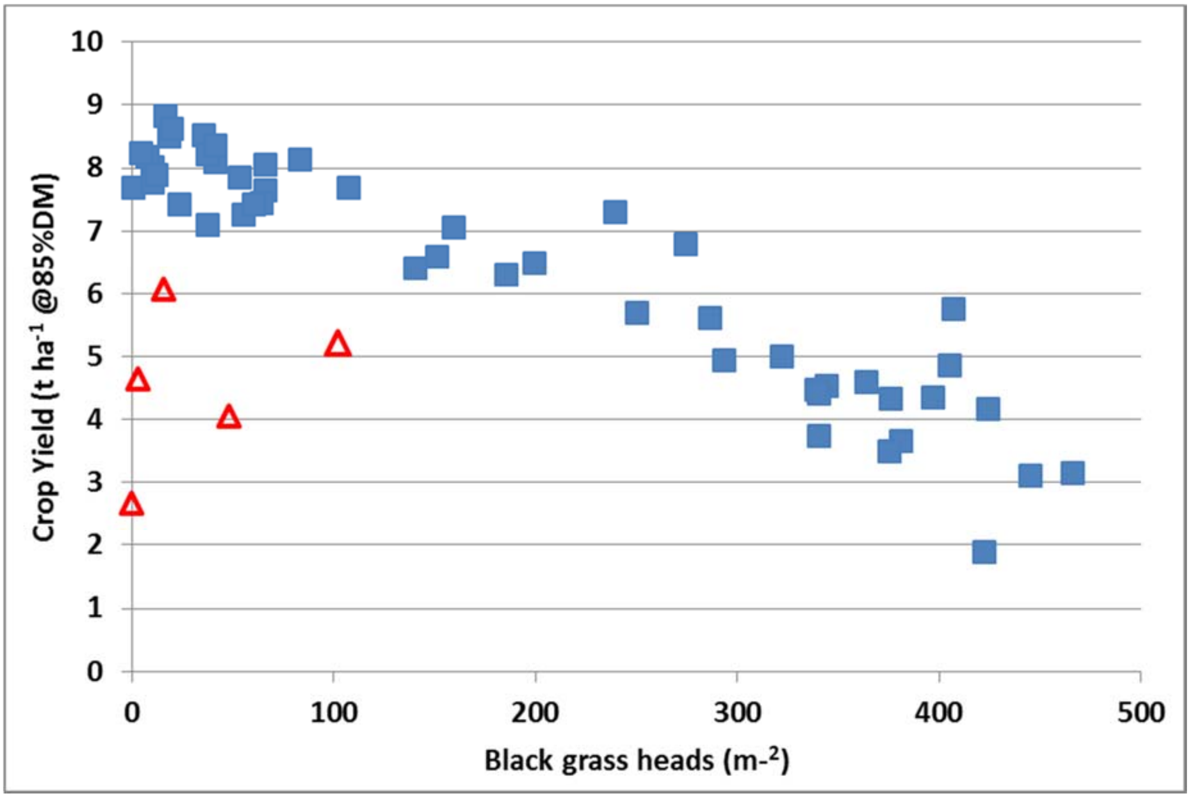

Figure 5. A scatter plot of individual plot values for black-grass heads (m^{-2}) related to eventual crop yield ($t.ha^{-2}$). Five plots are highlighted as open triangles where the crop yield is low relative to the black-grass population observed – in these plots crop establishment was particularly poor and they were removed from subsequent analysis. Simple linear regression of the relationship between black-grass head density and crop yield results in the best fit relationship y = 0.0108x + 0.839 with an R^2 of 0.84.

A simple linear regression using the data presented in Figure 5 would indicate that, on this site, 100 heads of black-grass equated to reduction of $1.08t.ha^{-1}$ in crop yield. It is important to note that the crop yield in this field trial was almost entirely determined by black-grass population level; other factors such as seed rate and sowing date seemingly having much less effect (including other factors into a regression model did not statistically significantly improve the ‘fit’).

4.10. Modelling using data derived from the field experiments

The main aim of the modelling work was to investigate the consequences of delayed autumn sowing, spring cropping, higher seed rates and differential pre-emergence herbicide efficacies on the additional level of control required from post-emergence herbicides to prevent black-grass populations increasing. This is particularly relevant in a situation, such as exists now, where the efficacy of most post-emergence herbicides is declining as a direct consequence of increasing herbicide resistance.

Baseline scenario: a potential black-grass population of **100 plants m^{-2}** in a wheat crop sown in mid-September with an objective of reducing this to a maximum of **3 surviving black-grass plants m^{-2} in spring**. The 2010 model would predict that 100 black-grass plants m^{-2} would produce 553 heads m^{-2} if left untreated. **Thus a reduction of 97% in black-grass plant density is required which is the typical level of control required to prevent black-grass populations increasing in non-inversion tillage systems** (Moss *et al.*, 2010). On average, a density of 12 black-grass plants m^{-2} gives a winter wheat yield loss of 5%, and this density is often quoted as a threshold at which increased return roughly equates with the cost of control (herbicide + application) (Marshall *et al.*, 2003). However, this is an average value, so higher yield losses would be expected in 50% of fields and this threshold is purely related to crop yield and takes no account of the longer-term implications of seed return. Thus it is sensible to incorporate an insurance element into any such threshold, which is why an objective of less than 3 surviving black-grass plants m^{-2} in spring is a more appropriate target.

4.10.1. Results of modelling exercises

The scenarios assume an initial, potential black-grass population of 100 plants m^{-2} and clearly at higher potential populations, higher levels of control would be needed to achieve < 3 surviving black-grass plants m^{-2} in spring. Conversely, at lower infestations, levels of control could be lower. The ability to achieve adequate control from post-emergence herbicides will depend very largely on the specific herbicide used, the resistance status of the black-grass population and the effectiveness of spray application, especially timing.

The outcomes of the different scenarios are summarised in Table 19.

Table 19. Control needed from post-emergence herbicides to achieve an overall level of 97% control in seven different scenarios involving sowing date, seed rate and pre-emergence herbicides.

Scenario	Winter wheat sowing data	Seed rate	Control from pre-em herbicide	Control needed from post-em herbicide
1	Mid-September sowing	Medium	No pre-em herbicide	**97%**
2	Mid-September sowing	Medium	Pre-em herbicide (**47% control**)	**95%**
3	Early – mid-October sowing – **33% less black-grass**	Medium	Pre-em herbicide (**73% control**)	**83%**

4	Early – mid-October sowing – **33% less black-grass**	High	Pre-em herbicide (**73% control**) + factoring in **29% fewer heads/plant due to seed rate**	**77%**
5	Late October sowing – **62% less black-grass**	Medium	Pre-em herbicide (**69% control**) + factoring in **25% fewer heads/plant due to drill date**	**66%**
6	Late October sowing – **62% less black-grass**	High	Pre-em herbicide (**69% control**) + factoring in **25% fewer heads/plant due to drill date** & **29% fewer heads/plant due to seed rate**	**53%**
7	Spring wheat sown in mid-March – **90% less black-grass**	Medium	Pre-em herbicide (**50% control**) + **factoring in 68% fewer heads/plant, relative to DD2**	**None required**

- Note that the % control values used in the winter wheat modelling exercise and shown in the table were **actual, mean values from the five field experiments**, so are realistic values, not just theoretical estimates. (See Tables 8, 9, 11 & 12). The values used for the spring wheat modelling scenario (90%, 50% and 68%) are slightly different to those found in the experiments and presented in the results tables (92%, 55% & 73%), as the finalised trial information was not available when the modelling exercise was done. This does not affect the outcome.
- In practice, values will vary between fields and years for a variety of reasons, but these results should provide good indicators of the control challenges and possible solutions.

Comments on the different scenarios (Table 19).

- In scenarios 1 & 2, where sowing takes place in mid-September, the level of control needed from a post-emergence herbicide (95% – 97%) is unlikely to be achieved on resistant black-grass populations, even following a pre-emergence treatment. This reflects the current practical problem on many farms.
- Delaying autumn sowing until early – mid-October reduces the potential black-grass infestation and using the same pre-emergence herbicide programme as in scenarios 1 & 2 gives improved control at this later timing. In this scenario 83% control is required from post-emergence herbicides, which is potentially achievable on partially resistant populations (Scenario 3).

- Using a higher crop seed rate increases crop competition and reduces the amount of black-grass seed return which has longer-term benefits. Using this in combination with delayed autumn sowing until early – mid-October and the same pre-emergence herbicide programme reduces the level of control required from post-emergence herbicides to 77%. This improves the chances of achieving adequate control of partially-resistant populations (Scenario 4).
- In Scenarios 5 and 6, drilling is delayed until late October which reduces the potential black-grass infestation even more. While no additional control from the pre-emergence herbicide occurs, black-grass produces fewer heads per plant, and consequently less seed return. In Scenario 6, this effect is even larger due to greater competition from the higher crop seed rate used. In these two scenarios, the level of control required from post-emergence herbicides is 53% – 66%. Delaying drilling this late is risky, but increases the chance of achieving adequate control of resistant populations.
- Scenario 7 involves sowing spring wheat in mid-March and, while based on less experimental data, highlights the benefit of the reductions in the potential black-grass infestation and seed return. In this situation a 50% control from pre-emergence herbicides is sufficient to reduce black-grass populations to less than 3 plants m^{-2} and no post-emergence herbicide is required. However, the efficacy of pre-emergence herbicides is likely to vary greatly depending on soil moisture and more spring emergence may occur on individual fields. Hence consistency may vary between years due to other factors and more studies are required on the resilience of spring cropping especially in relation to cultivation strategy, crop, sowing date and herbicide choice.
- It is clear that even with delayed drilling and use of higher seed rates, obtaining adequate control of highly resistant populations is unlikely unless at least 50% control can be achieved with post-emergence herbicides.
- Where severe resistance results in complete failure of post-emergence herbicides, greater reliance would need to be placed on pre-emergence herbicides. For Scenarios 4 & 6 above, assuming no post-emergence herbicides were used at all, the control needed from pre-emergence herbicides would need to be 94% and 85%, respectively. These levels may be achievable by ‘stacking’ multiple herbicides in favourable years when there is adequate moisture, but are very unlikely to be achieved consistently over a period of years, especially in dry autumns which may substantially reduce pre-emergence herbicide efficacy. In addition, all pre-emergence herbicides are affected by resistance which is likely to increase in the long term, although at a slower rate than commonly occurs with post-emergence herbicides.
- Spring-sown wheat appeared to be a good solution due to the substantial reduction in black-grass plants emerging compared with September-sown wheat. This more than compensated for the modest control (50%) achieved by pre-emergence herbicides.

However, with severe infestations, even a 90% reduction may mean a substantial number of black-grass plants emerging in spring crops and pre-emergence herbicide efficacy is dependent on soil moisture, so can be variable in the spring. In addition, a higher proportion of spring emergence may occur on individual farms than we recorded in our trials, establishing spring crops on heavy land may be problematical and spring-sown crops may be less attractive financially.

Comments on the different scenarios (Figures 6 & 7).

- In Figure 6, the effect of delaying winter wheat sowing by about three weeks from mid/late September to early/mid-October was modelled over an 8 year period. The use of a robust herbicide programme was assumed giving 83% and 89% control of black-grass plants, respectively, at the two sowing dates. These are the actual mean values achieved in the five field experiments (Table 9). In this example, no allowance was made for the reduced black-grass population and the reduced seeds per head (and consequently seed return) that occur with later sowing. The results show that a seemingly small increase in herbicide performance of 6%, as a consequence of delayed sowing, can have a substantial impact on populations but did not prevent populations increasing. This highlights the importance of maximising control from herbicides.

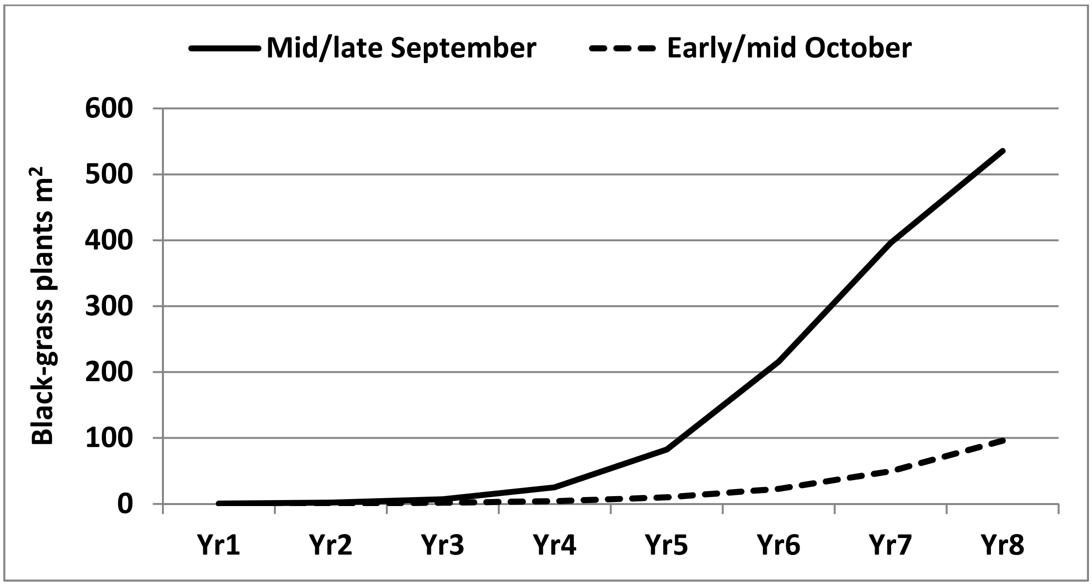

Figure 6. Effect of delaying winter wheat sowing by about three weeks from mid/late September to early/mid-October: model predictions of black-grass plants m^{-2} over an 8 year period in which a robust herbicide programme was used giving 83% and 89% control of black-grass plants, respectively, at the two sowing dates. In this example, the reduced black-grass population and the reduced seeds per head (and consequently seed return) that occur with later sowing are *not* factored into the modelling.

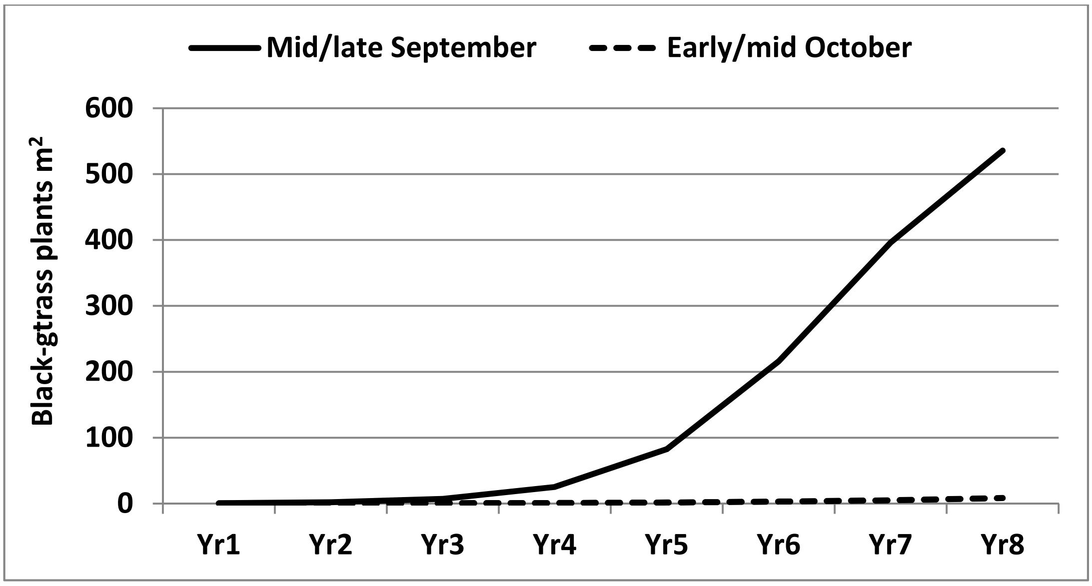

Figure 7. Effect of delaying winter wheat sowing by about three weeks from mid/late September to early/mid-October: model predictions of black-grass plants m^{-2} over an 8 year period in which a robust herbicide programme was used, as in Figure 6. In addition, the later sowing date factors in the reduced black-grass population and the reduced seeds per head (and consequently seed return) which occur with later sowing, as well as the better control from the herbicide programme.

- In Figure 7, in addition to the use of a robust herbicide programme giving 83% and 89% control of black-grass plants, respectively, at the two sowing dates, the reduced black-grass population and the reduced seeds per head (and consequently seed return) which occur with later sowing were included in the modelling exercise. This demonstrates clearly the significant additional benefit achieved from the reduced black-grass population and reduced seed return in combination with the better herbicide performance associated with delayed sowing. Although not obvious in Figure 7, the black-grass populations were still increasing at the later sowing date, but slowly.

4.11. Herbicide application timing and control

It is important when discussing drilling date and herbicide performance not to confuse later herbicide application as a consequence of delayed drilling with herbicide applications which are delayed relative to the emergence timing of weed and crop. In the field trial work presented here, when herbicides were applied at a later calendar date they were still applied at the correct application timing relative to crop and weed emergence (applied as true pre-emergence herbicides). To reinforce this point we have reviewed herbicide performance trials work conducted by NIAB over the period 2012 to 2015 (a sub-set of the complete dataset is presented here). These field trials consisted of two drilling dates (‘September’ and ‘October’). The ‘September’ drilled plots were established between September 7th and 20th and the ‘October’ drilled plots were all at least 3 weeks later at each site ranging from October 14th to 28th. At each drilling date the herbicides were applied at two timings; one at a true pre-emergence timing and the second a peri-emergence or very early post-emergence timing. The 'pre-emergence' timing application was always within 48 hours of the crop drilling with one exception where the application was 4 days after drilling. The 'peri-emergence' timing varied between 5 and 21 days after the pre-emergence application depending on the conditions at each site and the opportunities to spray. In all the trials the peri-emergence timing occurred after cotyledons of black-grass had begun to emerge and before the majority of the population had begun to produce the first true-leaf. Three trials were conducted in 2013/14; one at Ketteringham (Norfolk), a second at Hardwick (Cambridgeshire) and the third at Wragby (Linconshire.). A further two trials were conducted in 2014/15; at Hardwick and Wragby.

Figure 8 summarises the percentage control data (of black-grass plants) observed for two key treatments in the trial series. A mixture of flufenacet (240 g a.i. ha^{-1}) + pendimethalin (1200 g a.i. g a.i. ha^{-1}) ('Crystal @ 4.0 l ha^{-1}) and diflufenican (100 g a.i. ha^{-1}) ('Hurricance' @ 0.2 l ha^{-1}) was used in all cases.

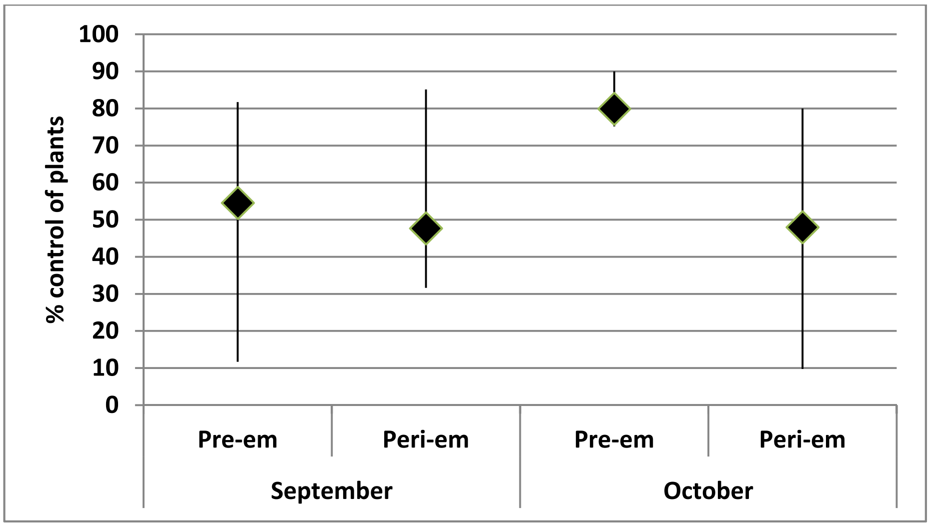

Figure 8. % control of black-grass plants observed in a trial series comparing herbicide performance (4.0 l ha^{-1} of 'Crystal' + 0.2 l ha^{-1} of 'Hurricane') at two drilling dates and two application timings. The (diamond) markers indicate the average % control and the vertical bars indicate the range (minimum and maximum) of control observed between the sites. For each average value n = 5 trials.

At the pre-emergence timing not only did the average % control increase with later drilling, by some 25%, but just as significantly the level of control observed became much more consistent. This improvement in herbicide performance for a month's delay in crop establishment is very similar to the mean value (26%) recorded for the five field trials which comprised the main part of this project report.

The other important result from this additional trial series is the significantly reduced control as a consequence of delaying herbicide application from a true pre-emergence timing. This effect was most marked in the later, October-drilled plots. In the September-drilled plots there was a single occasion (of the 5 included in the summary) where a delay produced better control – this was in the most extreme set of conditions in 2013/14 – but overall herbicide control was maximised by ensuring the herbicides were applied pre-emergence and avoiding delays in application. The reduction in control of black-grass plants as a consequence of delaying application was ~7% on average in the September and ~32% in the October-drilled crops.

The potential for variability in the effectiveness of pre-emergence herbicides is well demonstrated by these data; the herbicide used here (a tank-mix) provided 90% control in one situation and less than 10% in another. There may be a temptation for the grower or advisor, having already drilled a crop and faced with conditions where herbicide performance may be compromised, to delay herbicide application in the hope that conditions will improve. These data help to demonstrate that, in all but the most extreme situations, once the crop has been drilled then pre-emergence application of the herbicide become a priority in order to maximise weed control.

5. Discussion

This series of five field experiments, and associated modelling studies, produced some excellent information of direct relevance to a more integrated approach to combatting multiple-resistant black-grass in arable crops. The experimental design, having pairs of untreated and herbicide-treated sub-plots for all treatments, was very successful and allowed the effects of sowing date and crop seed rate to be assessed both in isolation and in combination with a robust herbicide strategy, which is clearly a more realistic scenario. This approach has rarely been used before.

The mean effects of delaying sowing winter wheat from mid/late September to early/mid-October over the five field trials are summarised in Table 20. This includes some relevant, but older, data on crop yields.

Table 20. Advantages in terms of control of black-grass achieved by delaying sowing of winter wheat from mid/late-September to early/mid-October. Means of five field trials.

	Effect of delaying drilling by approx. 3 wks from mid/late-September to early/mid-October	Range between trials	% of trials giving a positive result
Black-grass plants m^{-2}	**33% less**	-41 to 78%	80%
Black-grass heads $plant^{-1}$	**49% less – and a similar reduction in seed return**	-15 to 84%	80%

Additional control from pre-em herbicides	**26% more** (from 47% in mid/late September)	5 to 45%	100%
Impact on crop yield (3 trials, 1979 – 82)*	**Black-grass plants 55% less competitive (late Sept v late Oct)**	7 to 75%	100%

* from Moss (1985).

Thus, this series of experiments not only identified, but more importantly **quantified**, the **four** benefits of delayed autumn sowing which:

- **will usually result in less black-grass in the crop** (as more can be destroyed before sowing)
- **will typically result in fewer black-grass heads per plant** (and thus less seed return)
- **will generally result in better control from the herbicide programme** (as conditions for pre-emergence residual herbicides will usually be more favourable for activity – more soil moisture)
- **will normally result in black-grass being less competitive** (a consequence of less tillering)

Note that most of these benefits come from delaying sowing by about three weeks from mid/late September to early/mid-October, with additional, but relatively smaller, benefits from further delaying sowing until late October.

It must be stressed that these are the *average* effects recorded, and that they will vary between fields and years, as the range between trials show. Many factors will affect the levels of control in individual fields, such as weed emergence pattern, soil moisture and conditions (especially for pre-emergence herbicides), resistance status (especially for post-emergence herbicides) and the specific herbicide programme used and its timing. Some of these factors are outside of the farmer's control (e.g. the weather). Predicting herbicide efficacy at the individual field scale continues to be a considerable challenge and is a subject where more research could pay dividends. However, these results are based on a series of realistic field trials, which produced some very powerful and convincing evidence of the overall benefits of delaying autumn sowing of winter wheat as part of a strategy to improve control of black-grass by non-chemical means.

The 33% reduction in black-grass plants m^{-2} due to delayed sowing is remarkably similar to the 31% average value recorded for 19 previous experiments included in the review of Lutman *et al.*, (2013). This indicates that the five experiments included in this project produced results which are relevant and broadly applicable and by no means atypical.

The most important finding was the better black-grass control achieved by the pre-emergence herbicide programme when applied in later-sown crops. This mean benefit, an additional **26%** control from the same herbicide programme (flufenacet+diflufenican plus prosulfocarb), is substantial, especially when compared to the typical 10 – 20% increase achieved when adding an additional herbicide to a pre-emergence 'stack' (Stobart, 2009; Stobart & Orson, 2011). Although the precise reasons have not been investigated, it is probable that this is a consequence of increased soil moisture and lower temperatures at later sowing dates. This **26%** benefit is remarkably similar to the **25%** and **29%** mean benefits recorded, respectively, in the additional five NIAB trials and predicted (in average rainfall conditions) from a model based on data from 375 field trials in which flufenacet-based herbicides were used (Hull *et al*., 2014). This remarkable consistency in results obtained from two sets of five detailed trials, incorporating different sowing dates, and a much larger number of herbicide efficacy trials each sown at a single date between 2001 and 2013, is impressive and considerably enhances the credibility of the findings. These results show that the better control from pre-emergence herbicides can be at least as an important factor as the direct effect of delayed sowing at reducing black-grass populations. We believe this is a novel and important practical finding although it needs validating with other pre-emergence herbicides.

Increasing seed rate helped suppress black-grass by up to **29%** and this figure is similar to the 26% average value recorded in the review of Lutman *et al*., (2013). However, it was clear that higher seed rates were less effective at reducing black-grass than delayed autumn sowing, which was a much more effective strategy overall due to a combination of reduced black-grass plant populations and better herbicide efficacy.

Seed return was estimated, averaging 87,959 seeds m^{-2} on untreated sub-plots at the first sowing date, highlighting the very high seed production potential of black-grass. However, there was no evidence that the very laborious and time consuming assessments involved, produced results that were any better in terms of quantifying treatment effects than those based on head assessments alone. This was a useful finding as it could save a considerable amount of time in similar future investigations involving black-grass, although assessing seed return is important in other studies, such as those involved with population dynamics over several years.

Spring-sown wheat appeared to be a good solution due to the substantial (**92%**) reduction in black-grass plants emerging compared with September-sown wheat and the lower number of heads and seed produced per plant. These factors more than compensated for the modest control (**55%**) achieved by the pre-emergence herbicides (pendimethalin+prosulfocarb) used in spring wheat. However, with severe infestations, even a 90% reduction in emergence may mean a substantial number of black-grass plants emerging in spring crops and pre-emergence herbicide efficacy is dependent on soil moisture, so can be variable in the spring. In addition, a higher proportion of spring emergence may occur on individual farms than we recorded in our trials, establishing spring crops on heavy land may be problematical and spring-sown crops may be less attractive financially. Hence consistency may vary between years due to other factors and more studies are required on the resilience of spring cropping especially in relation to cultivation strategy, crop, sowing date and herbicide choice.

The fact that black-grass plants emerging in spring wheat had fewer heads per plant and fewer seeds per head suggests that they are less competitive on an individual plant basis than black-grass plants emerging in autumn sown crops. However, there appears to be little, if any, published data on the effect of black-grass on the yield of spring-sown wheat or barley in contrast to a very considerable amount relating to autumn-sown winter wheat.

The modelling studies were a particularly useful component of this project as they used actual mean values from the experimental programme rather than theoretical estimates. The outputs showed that, even with delayed drilling and use of higher seed rates, obtaining adequate control of highly resistant populations is unlikely unless at least 50% control can be achieved with post-emergence herbicides. Where severe resistance results in complete failure of post-emergence herbicides, greater reliance would need to be placed on pre-emergence herbicides. For the scenarios which featured late October drilling with either medium or high crop seed rate (Scenarios 4 & 6), if one assumed no post-emergence herbicide was used at all, the control needed from pre-emergence herbicide would need to be 94% and 85%, respectively. These levels may be achievable by ‘stacking’ multiple herbicides in favourable years when there is adequate moisture, but are very unlikely to be achieved consistently over a period of years, especially in dry autumns which may substantially reduce pre-emergence herbicide efficacy. In addition, all pre-emergence herbicides are affected by resistance which is likely to increase in the long term, although at a slower rate than commonly occurs with post-emergence herbicides (Moss & Hull, 2009). The model was based on information collected in winter wheat crops, but should be broadly applicable to other autumn-sown crops such as oilseed rape and winter beans, although recognising that sowing date and the effects of crop competition will differ to some degree.

These findings show that delayed autumn drilling and use of higher seed rates, in conjunction with a robust herbicide programme, can make a very useful contribution to reducing the threat from herbicide-resistant black-grass. However, these measures alone will not be sustainable in intensive arable rotations if resistance continues to increase, especially to the pre-emergence herbicides but also, potentially, to glyphosate. The results also show that spring cropping has much potential but can be a difficult option especially on the heavy soils which greatly favour black-grass. There are no easy options or ‘quick fixes’, but a return to more balanced rotations and a move away from ever-earlier drilling must be the longer-term goal – a reversal of the trends that have occurred over the last 40 years (Figures 2 & 3). Even if new modes of action are introduced, it is entirely possible that some of the resistance mechanisms that have already evolved, especially enhanced metabolism, will affect their performance. There are many precedents for this. Even if not, there is a high risk that resistance will subsequently evolve, as black-grass appears to be a particularly adaptable weed in this respect – one of the world's most resistance-prone species. There really is no other option than greater use of non-chemical control methods and less reliance on herbicides. Delayed autumn sowing and higher seed rates are an important component of a more sustainable integrated weed management programme and this project has gone a long way in quantifying their contribution.

Critically, this series of experiments quantified these benefits, not only in terms of the direct effect of delayed sowing and higher seed rates, but also in the more realistic context of a robust herbicide programme. This makes the outputs of this project much more credible, and relevant, than most previous studies on this topic. The results showed that the better control from pre-emergence herbicides is at least as an important factor as the direct effect of delayed sowing at reducing black-grass populations. We believe that this was a novel, very important and highly practically relevant finding.

Further R & D requirements

- **A better assessment of the risks associated with delayed autumn sowing at the individual field scale – can risks be better assessed utilising knowledge of location, soil characteristics, resistance status, rainfall and other weather parameters?**
- **How best to utilise the period between cereal harvest and sowing the next crop in order to minimise black-grass infestations within the crop – how much can emergence patterns of black-grass be manipulated by cultivations and other means?**
- **Confirmation that the improved efficacy of pre-emergence herbicides at later sowing dates applies to other herbicides commonly used at this time – do they all respond similarly?**
- **Studies on pre-emergence herbicides to explain why efficacy is so variable in both autumn-sown and spring-sown crops – can an understanding of this characteristic result in better and more consistent control?**
- **The best cultivation strategy, crop, sowing date and herbicide choice for spring-sown crops – how to maximise the benefit for controlling black-grass?**
- **How much do grass-weeds, such as black-grass, reduce the yield of spring-sown crops – can you tolerate more black-grass in spring crops?**
- **Resistance to pre-emergence herbicides – how quickly does it increase?**
- **The threat from glyphosate resistance – can black-grass evolve resistance?**

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