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A review of the effects of crop agronomy on the management of *Alopecurus myosuroides*

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Summary

This study reviews 52 field experiments, mostly from the UK, studying the effects of cultivation techniques, sowing date, crop density and cultivar choice on *Alopecurus myosuroides* infestations in cereal crops. Where possible, a statistical meta-analysis has been used to calculate average responses to the various cultural practices and to estimate their variability. In 25 experiments, mouldboard ploughing prior to sowing winter cereals reduced *A. myosuroides* populations by an average of 69%, compared with non-inversion tillage. Delaying drilling from September to the end of October decreased weed plant densities by approximately 50%. Sowing wheat in spring achieved an 88% reduction in *A. myosuroides* plant densities compared with autumn sowing. Increasing winter wheat crop density above 100 plants m^{-2} had no effect on weed plant numbers, but reduced the number of heads m^{-2} by 15% for every additional increase in 100 crop plants, up to the highest density tested (350 wheat plants m^{-2}). Choosing more competitive cultivars could decrease *A. myosuroides* heads m^{-2} by 22%. With all cultural practices, outcomes were highly variable and effects inconsistent. Farmers are more likely to adopt cultural measures and so reduce their reliance on herbicides, if there were better predictions of likely outcomes at the individual field level.

Keywords: black-grass, IWM, cultural control, cultivations, sowing date, seed rate, cultivars, spring cropping.

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Introduction

Since the initial discovery of selective herbicides in the 1940s and 1950s, farmers have become increasingly dependent on herbicides to manage weeds in arable crops. However, fewer herbicides are available now in Europe due to past EU regulatory actions (Directive 91/414/EEC), and further reductions are anticipated from the latest pesticide authorization regulations (EC/1107/2009) and the Water Framework Directive (2000/60/EC; Anon, 2011a,b; Stark, 2011). In addition, there has been a lack of development of herbicides with new modes of action.

The recent EU Thematic Strategy for Pesticides includes the Sustainable Use Directive (2009/128/EC), which promotes the use of integrated pest management and requires that priority be given to non-chemical methods of crop protection (Stark, 2011). This means that farmers will be expected to place greater reliance on non-chemical weed control measures and reduce their dependency on herbicides.

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The situation in the UK has become particularly critical for weed control in winter cereal crops for several reasons:

- cereals [wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.)], mainly sown in September or early October, dominate most arable rotations and accounted for 64% of the area cropped in the UK in 2011 (Defra, 2011),
- common alternative break crops such as oilseed rape (*Brassica napus* L.) and field beans (*Vicia faba* L.) are also predominantly autumn sown,
- the major weed problem in winter cereals is *Alopecurus myosuroides* Huds. (black-grass), which is particularly favoured by rotations dominated by autumn-sown crops (Elliot *et al*., 1979) and
- several key herbicides for grass weed control have recently been withdrawn from the UK market as a consequence of regulatory action (e.g. isoproturon, trifluralin), and herbicide resistance in *A. myosuroides* is widespread, making successful control with herbicides increasingly difficult (Moss *et al*., 2011).

Alopecurus myosuroides is the most important herbicide-resistant weed in Europe, occurring in at least 10 countries (Moss *et al*., 2007). In the UK, it is an extremely common annual grass weed throughout the main arable areas of England (Preston *et al*., 2002) and is the major target of weed control in autumn-sown crops. It is a competitive weed, with the potential to produce many seeds, and if not adequately controlled, infestations can increase rapidly and cause substantial yield losses (Moss, 1987b, 1990; Blair *et al*., 1999). Consequently, high levels of control are required to prevent populations from increasing (Moss *et al*., 2010). Control since the 1970s has been highly dependent on the continuing availability of a range of effective herbicides, including chlorotoluron, isoproturon, fenoxaprop, clodinafop, flupyrsulfuron and mesosulfuron + iodosulfuron in cereals; and propyzamide, fluazifop-P-butyl, propaquizafop and cycloxydim in oilseed rape (Lainsbury, 2012). In the UK, resistance has been confirmed to all these herbicides, with the exception of propyzamide (Moss *et al*., 2007). The decline in the number of available products and the increase in resistance have made this dependency on herbicides increasingly unsustainable. Consequently, there is increasing interest in integrated weed management with the aim of exploiting crop agronomy to decrease grass weed infestations and thus reduce the dependence on herbicides.

Potential cultural practices are listed by Moss and Clarke (1994): mouldboard ploughing, crop rotation, spring cropping, delayed autumn drilling, stubble hygiene, competitive crops and in-crop cultivations. A major challenge is to quantify the effectiveness and reliability of these different practices at controlling *A. myosuroides,* in winter cereals. This should encourage a more rational appraisal of the potential of cultural control to substitute, at least partly, for herbicides. A considerable number of research projects carried out over the last 30 years have explored the effects of crop agronomy on *A. myosuroides* but, to date, no one has integrated all the published information and calculated overall mean responses and estimated the likely variation. This is the primary objective of this study. Emphasis has been placed on analysing the impacts of changing cultivation practices, drilling dates, crop density and crop cultivars.

Materials and methods

Data collection and collation

As far as possible, all published data on the effects of cultural practices on *A. myosuroides* have been identified and collated. This work has focussed on UK data, but some information has also been collected from Germany and France. The collated information fell into three categories:

1. Research reports from the UK, published in refereed journals and conferences, which include statistical comparisons between treatments and relevant standard errors.
2. Research reports that did not include relevant statistics, and data from elsewhere in Europe.
3. Reports in farmer-focussed publications that included mean values for appropriate cultural practices but little further information ('grey data').

All the experiments included in this study studied the effects of treatments on *A. myosuroides* growing in winter cereals, mainly winter wheat, but there were a few experiments with winter barley. Five experiments also compared autumn- and spring-sown wheat. The studies reported the effects of the treatments on *A. myosuroides* plant numbers m^{-2} in the winter or early spring and/or head numbers m^{-2} in the following summer.

Soil cultivation experiments

The 25 field experiments included in the meta-analysis compared non-inversion cultivation with mouldboard ploughing and direct drilling, although some experiments only had two of the three treatments. Details are given in Appendix 1. Non-inversion cultivation was achieved by either tine or disc cultivation or both. Information on the depth of cultivation was not always included in the papers but, typically in the UK, non-inversion tillage would be to 5–15 cm depth, whilst mouldboard ploughing would be to 20–25 cm depth. The key difference is the much greater soil inversion achieved by mouldboard ploughing compared with non-inversion tillage (Cousens & Moss, 1990). Only one paper (Pollard *et al.*, 1982) compared two depths of non-inversion tillage. Direct drilling resulted in minimal disturbance of the soil and shed seeds. Further data sets from France and Germany are discussed in the results, but are not included in the meta-analysis.

Sowing date experiments

In all 19 experiments included in the meta-analysis, the crop was sown at two or three dates between September and January (see Appendix 2 for details). In all experiments, plant numbers m^{-2} were recorded in the winter and, in 17, head numbers m^{-2} were also recorded in the following summer. Additionally, information that could not be included in the meta-analysis was also collected from published reports from England, France and Germany.

Spring cropping experiments

Five experiments compared the densities of *A. myosuroides* present in winter wheat sown between September and January with densities in spring wheat sown between March and 1 May (Moss & Hull, 2012). Because of the limited amount of data, no overall analysis has been attempted.

Crop density experiments

Six experiments compared the competitive effects of winter wheat sown at two or three densities (range 64–508 wheat plants m^{-2}) on the numbers of *A. myosuroides* plants and heads m^{-2} in the crop (see Appendix 3 for details). Some reports included only the seed rate sown, whilst others recorded the actual crop densities established. For the meta-analysis, the number of crop plants m^{-2} was needed. Where this was not included in the reports, the seed rates have been multiplied by an establishment factor of 0.67. This value is taken from the mean crop establishment calculated for wheat sown in September and October in a comprehensive review of the effects of seed rate on the yields of winter wheat (Blake *et al.*, 2003). Data from a further ten seed rate trials conducted mainly by UK agrochemical distributors are also presented, but were not included in the meta-analysis (Appendix 4).

Crop cultivar experiments

Reports of eight experiments have been included, but a full meta-analysis of the disparate data sets was not possible. All experiments compared cultivars on the basis of either *A. myosuroides* heads m^{-2} or the percentage reduction in heads by the tested cultivars compared with a standard reference cultivar. The numbers of cultivars compared in each experiment varied from two to nineteen (Appendix 5). Most experiments compared cultivars of winter wheat, although two experiments also included comparisons of cultivars of winter barley.

Data analyses

Wherever possible, detailed statistical analyses have been carried out on all the available data (Table 1, Appendices 1-3). For these combined analyses, it was necessary to use means from analysis of a $\log_{10}$-transformation of the count data, to deal with variance heterogeneity arising from differences in weed density between experiments. Some published papers only included untransformed means and standard errors. When necessary, we have contacted the authors, accessed the raw data and performed the appropriate analyses (generally analysis of variance) on the $\log_{10}$-transformed values, to generate the required standard errors. The experiments were all of a randomized block, split plot or factorial design with three or more replicates. Genstat (2011) was used to carry out all the analyses.

Cultivation data

The three treatments (mouldboard ploughing, non-inversion tillage and direct drilling) have been compared and standard errors of the overall $\log_{10}$ mean values (*A. myosuroides* plants or heads m^{-2}) calculated. The meta-analysis of the 25 experiments used a

Table 1 Details of sources of data included in meta-analyses (see Appendices 1–3 for data used)

	Number of experiments	Number of data sets	Data sources
Soil cultivation	25	67	Moss (1979, 1980, 1981, 1985a,b, 1987a, unpubl. obs., 2001), Pollard *et al.* (1982), Froud-Williams *et al.* (1983) and Cook *et al.* (2006)
Sowing dates	19	40	Moss (1985a), Tatnell (2001), Cook *et al.* (2006) and Moss and Hull (2012)
Seed rate	6	16	Moss (1985c, unpubl. obs., 2001, 2010)

linear mixed model with $\log_{10}$ plant or head numbers as the response variable. The fixed model contained an overall constant and effects for the three cultivation methods, using appropriate constraints. The random model contained three terms: (i) independent random trial effects with common variance to be estimated, (ii) independent random trial × treatment effects with common variance to be estimated and (iii) independent random effects with known variance derived from the SEDs for plot error. The final term reflects uncertainty in the treatment mean, based on within-trial variability. This is the same type of model as used by Paul *et al.* (2010) in a meta-analysis of wheat disease experiments, but with a simpler form of the Treatment × Trial interaction. Those authors used an unstructured variance matrix, which allowed for differing variances and covariances within, and between, treatments (across trials). The model described above is equivalent to a uniform covariance matrix, which has common variances and covariances across treatments. The Akaike Information Criterion (AIC) was used to compare the uniform with the more complex-unstructured (and intermediate) models and indicated no improvement from the use of the more complex models. The fitted model can be used to test the null hypothesis that, after accounting for differences in logged plant or head numbers between trials, there is no consistent underlying additive difference in $\log_{10}$ numbers due to the treatments.

Sowing date and crop density data

In the 19 sowing date experiments, the crop was sown at two or more drilling dates. Drilling date was defined as days from 31 August. The meta-analysis used $\log_{10}$-transformed mean numbers of *A. myosuroides* plants or heads m^{-2} for each drilling date on each experiment, along with their relevant standard errors. The meta-analysis again used a linear mixed model with the $\log_{10}$ plant (or head) numbers as the response variable. The model allowed the background logged number of *A. myosuroides* to differ between experiments and modelled the proportional change in logged numbers in response to drilling date assuming a common form of response across experiments. A smoothing spline function was used to model the response to the drilling dates, as this allows for non-linearity in the trend without having to pre-define the form of the curve. The fixed part of the model contained a constant and a linear component or trend in terms of drilling date (days from 31 August). The random part of the model had four terms: (i) smoothing spline across time to model response to drilling date, (ii) independent random trial effects with a common variance to be estimated, (iii) independent random residual effects with common variance to be estimated to account for deviations from the fitted curve and (iv) independent random effects with known variance derived from the SEDs for plot error. This final term reflects uncertainty in the treatment mean, based on within-trial variability. Predictions of the response were made daily commencing on 15 September. Confidence intervals (95%) were calculated for the comparison of each prediction. The responses after 15 September were expressed as a percentage of the numbers expected from drilling on 15 September.

The crop density data analyses of six experiments were based on the same framework as the crop drilling date data, but were less complex, as the response to crop density appeared linear on the $\log_{10}$ scale. Predictions of the response were made for crop densities between 100 and 350 wheat plants m^{-2}, in steps of 50 plants m^{-2}. Confidence intervals (95%) were calculated for the comparison of each prediction. *Alopecurus myosuroides* infestations at crop densities above 100 wheat plants m^{-2} were expressed as a percentage of the numbers expected at 100 wheat plants m^{-2}.

Cultivar data

The variable design and scale of the eight experiments meant that the data comparing cultivars were not amenable to a combined analysis, so all the data have been treated as being in categories (2) or (3). Two comparisons have been made: firstly, the advantage (in terms of percentage reduction in heads of *A. myosuroides*) in growing the most competitive cultivar compared with the mean of all cultivars tested, and secondly, the benefit of growing the most competitive compared with the least competitive cultivar. Mean values for the eight experiments have been calculated. Four of the experiments included the cultivars Hereward (poorly competitive) and Robigus (strongly competitive) as standards. So, for these experiments, the percentage decline in *A. myosuroides* heads m^{-2} arising from growing Robigus rather than Hereward has been calculated.

Results

Primary soil cultivations

The meta-analysis indicated a significant difference between the three cultivation methods (F-statistic 32.83 on 2,38 d.f., $P < 0.001$). Mouldboard ploughing reduced the number of *A. myosuroides* plants m^{-2} in the subsequent crop by 69% compared with non-inversion tillage (Table 2). In contrast, direct drilling appeared to slightly increase the density of *A. myosuroides* plants (by 16%) compared with non-inversion

Table 2 Average numbers of *Alopecurus myosuroides* plants m^{-2} following ploughing, non-inversion cultivation and direct drilling, based on a meta-analysis of data from 25 field experiments

	Non-inversion cultivation	Ploughing	Direct drilling	SED (38 d.f.)
Log_{10} mean	2.07	1.57	2.14	0.045
Detransformed mean (plants m^{-2})	118	37	137	
% Change		−69	+16	

cultivation, but this increase was not statistically signifi cant (Table 2). However, although there was strong evidence that mouldboard ploughing reduced the number of *A. myosuroides* plants, there was considerable variability in the data sets. Examination of the untransformed data (see Appendix 1) shows that in 18 of 20 experiments, mouldboard ploughing reduced *A. myosuroides* numbers by 12–96%, whilst in two experiments, it increased them by up to 82%, relative to non-inversion (tine/disc) tillage. This variation was even more marked in a comparison of non-inversion tillage with direct drilling, as 13 experiments showed there were more *A. myosuroides* plants after direct drilling (up to a maximum 344%), while in six others, it resulted in a decrease (up to 78%). It thus appears that although there was no mean response to direct drilling, it could triple the *A. myosuroides* population, or reduce it by three-quarters, in comparison with non-inversion cultivation.

The equipment used to achieve non-inversion cultivation in the experiments varied greatly from light tines to heavy discs, and consequently, the depth and amount of soil disturbance also varied. It has not been possible to analyse whether different non-inversion techniques have differing effects on *A. myosuroides* populations, because of the variability in the other agronomic factors in the experiments (sowing date, soil type, soil moisture, amount of crop residues). However, two experiments reported by Pollard *et al.* (1982) compared shallow tine cultivation (to 8 cm) with deep tine cultivation (to 16 cm). The data for the two experiments showed no difference in *A. myosuroides* plants m^{-2} after tine cultivation to the two depths (52 vs. 51 plants m^{-2} for 8 and 16 cm respectively), although mouldboard ploughing reduced *A. myosuroides* plant numbers by an average of 52% and direct drilling marginally increased them (by 5%).

The meta-analysis was also used to investigate the potential impact of the overall weed density on the relative effectiveness of different cultivation practices. It could be argued that the beneficial influence of mouldboard ploughing would be greater in heavily infested fields, where substantial numbers of freshly shed weed seeds would be present on the soil surface prior to burial. However, a grouping analysis where 'high weed density' sites (based on population density on non-inversion plots) were compared with 'low weed density' sites failed to detect any significant effects on the relative responses to the three cultivation techniques.

The UK data form the core of the analyses, but some relevant data have also been published in Germany and France on the response of *A. myosuroides* to cultivations. Hurle and colleagues concluded in three experiments that mouldboard ploughing would reduce *A. myosuroides* populations by 85% (Hurle, 1993; Knab & Hurle, 1988) compared with tine cultivation. The French long-term 'systems' experiment reported by Chauvel *et al.* (2009) includes comparisons of plots established by mouldboard ploughing and tine cultivation. However, as the plots also include variation in sowing date and cropping, it is difficult to extract the specific effect of tillage. The implications are that mouldboard ploughing achieved a 25–52% reduction in *A. myosuroides* density. So these French and German results broadly support the conclusions of the meta-analysis of the UK data that mouldboard ploughing was the most effective tillage practice.

Sowing date

The meta-analysis of all the sowing date data (19 experiments) showed that there was a statistically significant change in the number of *A. myosuroides* plants recorded as the sowing date of the winter wheat was delayed (*F*-statistic 44.33 on 1,18 d.f.: $P < 0.001$). The trend was of a decline in plant numbers from *c.* day 30 (end of September) through to day 90 (end of November) (Fig. 1A). The steepest decline occurred during October (days 30–60). However, there was considerable variability in the data, and it was only after the end of October that there were statistically significantly fewer plants. It appears that delaying drilling until the end of October would reduce *A. myosuroides* number by at least 50%, but it is unclear whether a delay until mid-October has much benefit. Further delay in drilling after mid-November did not seem to cause a further decline in *A. myosuroides* plant numbers, but there are few points on the graph at these dates and so the confidence in predicted responses is much weaker. It is clear that the greatest variability occurred from late September to mid-October (e.g. days 30–50).

The analysis of the *A. myosuroides* head numbers on 17 experiments shows a similar response to the

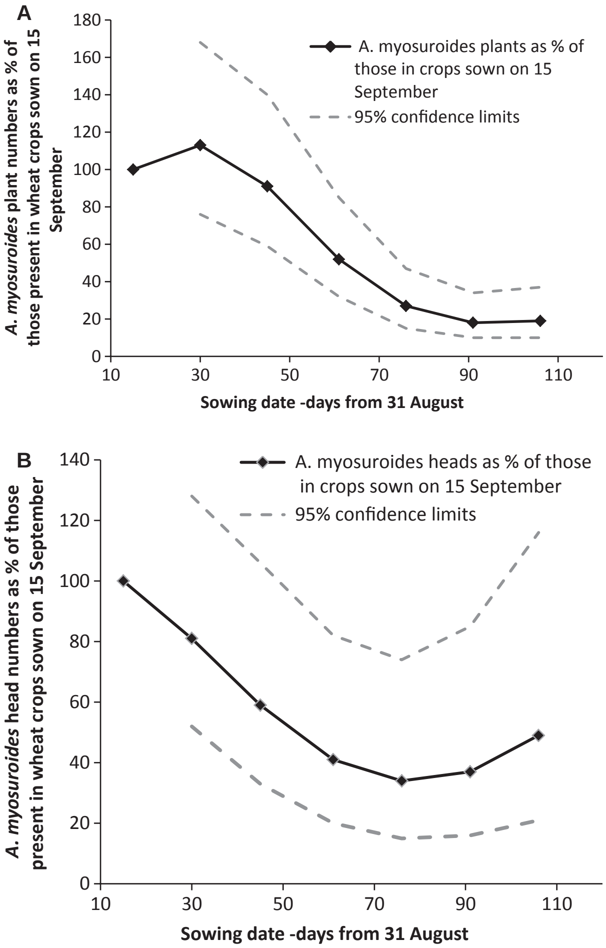

Fig. 1 Effect of sowing date on the number of *Alopecurus myosuroides* plants (A) and heads (B) m^{-2}. Data expressed as percentage of those present in crops sown on 15 September (with 95% confidence intervals).

plant numbers, but as the variability in the data was even greater, the meta-analysis indicated no significant effect of sowing date on weed head numbers (F-statistic 1.99 on 1,18 d.f.: $P < 0.18$) (Fig. 1B). The response curve indicates that there is probably a decline in head numbers following sowing during October, but there are indications of an increase again during November and December. There could be an interaction in these later drillings with potentially poorer crop establishment, which could have reduced the competition from the crop in the spring, thus encouraging greater tillering and head production from the *A. myosuroides* plants. This competitive response would not be apparent in the weed plant number assessments made during the winter, when there is less competition between the crop and weed (Moss, 1987b).

Other published data from England, France and Germany tend to support the view that delayed sowing reduces *A. myosuroides* plant numbers. Hurle (1993) reported that in a German experiment, delaying sowing from September to October decreased plant number by 72%. In contrast, Cussans (2009), working in England, only found a marked reduction in heads m^{-2} when sowing was delayed until November, as September and October sowings resulted in similar populations. Thurston (1964) reported that when winter wheat was sown in October, November or later, *A. myosuroides* densities increased over previous years, remained the same or declined respectively. The results of the Chauvel *et al.* (2009) systems experiment in France are a little equivocal. In the traditional winter cropping rotation, delayed tine cultivation and sowing (late September/early October vs. mid-/late October) reduced plant numbers in early years of the experiment, but in the later ones, when the infestation was low, this effect was no longer apparent. The meta-analysis and the corroborative data from Thurston (1964), Chauvel *et al.* (2009) and Cussans (2009) all indicate that a decline in plant number can be achieved, at least in some circumstances, by delaying sowing winter cereals until October, but consistent benefits appear to only arise when sowing is delayed until the end of the month, or even until November. This is a practice most farmers would be reluctant to adopt in the UK, especially on heavy soils, because of the risk of failing to sow the crop at all and the likely reductions in yield.

Spring cropping

Five experiments assessed the effect of two autumn and one spring sowing date on *A. myosuroides* populations in wheat crops, in the absence of any herbicide treatment (Moss & Hull, 2012). Much of the information from the two autumn sowings of winter wheat has already been incorporated into the meta-analysis described above, indicating a decline in *A. myosuroides* plants m^{-2} with delayed autumn sowing. The results of the five experiments re-emphasize the variability in the responses to delayed autumn drilling with results ranging from a 40% increase to an 81% decrease in weed plant numbers (Table 3). More importantly, the experiments also quantified the impact of delaying sowing wheat until the spring. Sowing spring wheat in March (or in one case, on 1 May) resulted in 78–96% reductions in *A. myosuroides* plant populations relative to wheat sown in September. The mean reduction in weed plant density was 88%. However, even an 88% reduction can leave substantial numbers of *A. myosuroides* plants, when the infestation has been severe. The 95% reduction achieved in 2005 still left 310 weed plants m^{-2} in the spring crop (Table 3).

Table 3 Effects of delayed autumn sowing of winter wheat and sowing a spring wheat crop on the numbers of plants of *Alopecurus myosuroides* emerging (plants m^{-2}) in five experiments (Moss & Hull, 2012)

Experiment	Sowing date	*A. myosuroides* plants m^{-2}	Percentage reduction (compared with earliest sowing)
Broadmead 2000/2001	21 September	860 ± 142*	–
	16 January	330 ± 80	62
	1 May	185 ± 35	78
Claycroft 2004/2005	27 September	6101 ± 559	–
	17 November	1152 ± 94	81
	17 March	310 ± 44	95
Warren 2009/2010	19 September	660 ± 77	–
	19 October	555 ± 45	16
	16 March	95 ± 7	86
Broadmead 2010/2011	16 September	649 ± 28	–
	7 October	141 ± 5.8	78
	17 March	25 ± 10.4	96
Warren 2011/2012	16 September	205 ± 27	–
	3 October	288 ± 13	−40
	15 March	26 ± 6.5	87

*Standard error of mean.

Crop density

In the six experiments included in the meta-analysis, there was no statistically significant relationship between winter wheat density and the number of *A. myosuroides* plants m^{-2} present during the autumn/winter. However, by the early summer, there was a significant effect of crop density on the number of *A. myosuroides* heads m^{-2} (F-statistic 25.62 on 1,13 d.f.: $P < 0.001$). The analyses indicated that increasing winter wheat seed rates from 100 to 200 or 300 plants m^{-2} decreased *A. myosuroides* head numbers by 17% and 32% respectively (Fig. 2A). The response up to the maximum crop densities studied (*c*. 350 plants m^{-2}) appeared almost linear ($y = 114 - 0.153x$), equivalent to a 15.3% reduction in weed head density for every additional 100 wheat plants m^{-2}. As the density of the wheat increased, the variability in the data, as shown by the 95% confidence limits, also increased, such that at 300 wheat plants m^{-2}, there was a range of 20% in the response of the *A. myosuroides* head reduction. This variability was partly due to the lack of data at the high crop densities, partly because of the nature of the analysis and partly because of the intrinsic variability in the weed's response to crop density (as also shown from the inclusion of the category (2) and (3) data in Fig. 2B, see below). *Alopecurus myosuroides* plant density was much less affected by crop seed rate than head density, which indicates that the main effect of increasing seed rate was in reducing the tillering ability of *A. myosuroides* plants and hence reducing the number of heads per plant. Sequential emergence counts on some experiments indicated little loss of *A. myosuroides* plants in winter and spring, even at high plant densities (Moss, unpubl. obs.).

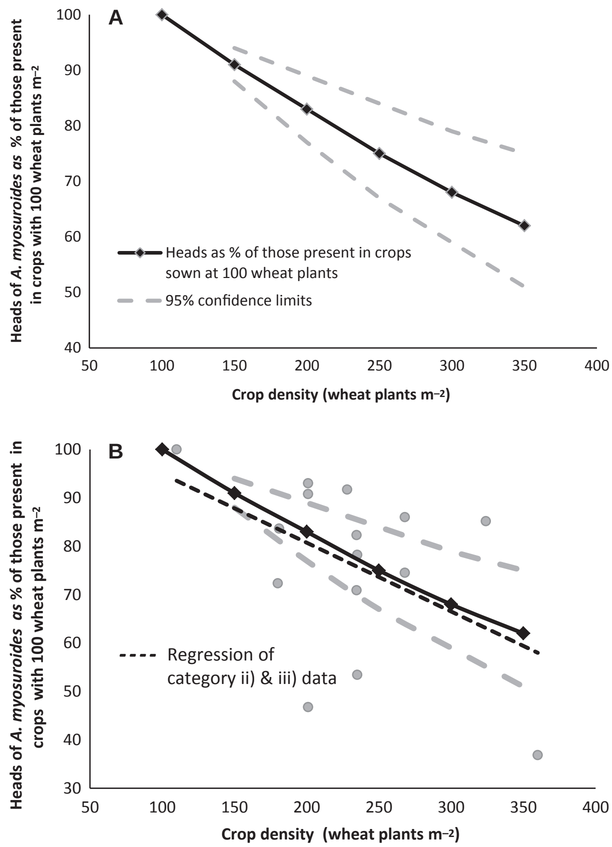

Fig. 2 Relationship between crop density and number of *Alopecurus myosuroides* heads m^{-2} expressed as a percentage of those present at 100 crop plants m^{-2} (plus 95% confidence intervals). (A) Data from six experiments used in the meta-analysis. (B) Values from 10 category (2) and (3) data experiments (●) and their overall regression line ($y = 109.2 - 0.142x$) superimposed on meta-analysis data from A.

Comparison of the conclusions of the meta-analysis with the data from the 10 category (2) and (3) experiments confirmed the same trend, despite the variability in the data. The mean of the lowest crop density in these 10 experiments was 110 plants m^{-2}, close to the 100 plant value used in the meta-analysis. A regression analysis showed that there was a linear increase in the percentage reduction in *A. myosuroides* head numbers as the density of the crop increased (Fig. 2B). Overall, there was a 14.2% reduction with every increase in 100 wheat plants m^{-2} (head numbers = $109.2 - 0.142x$ wheat density ($R^2 = 0.16$; $P = 0.075$). As is clear from the previous sentence, the data were highly variable and as a result the relationship does not quite reach 95% significance. However, both analyses indicated that there would be a *c*. 15% reduction in weed head numbers for every additional 100 wheat plant m^{-2} established above the baseline level (100 wheat plants m^{-2}).

Cultivar choice

The analysis of the eight category (2) and (3) experiments showed that there was a 30% mean reduction in heads m^{-2} of *A. myosuroides* when comparing the most competitive with the least competitive cultivar of winter wheat (Table 4). When comparing the most competitive cultivar with the average of all cultivars tested, the benefit declined to 22%. The range of responses was very high, 16–61% and 8–45% respectively, for the two comparisons, indicating that the predictability of the benefit from growing the more competitive cultivars is likely to be low. The reasons for the variability between experiments are not simply due to the different range of cultivars used in each experiment, as the variability remained substantial even when comparing the same cultivars, such as the competitive Robigus and the less competitive Hereward (Table 4). The four experiments that included these two cultivars showed that, on average, Robigus reduced the number of *A. myosuroides* heads (compared with Hereward) by 36% with a range of 9–61%. Other studies of Robigus and Hereward (Neuhoff *et al.*, 2004) indicated that the more competitive Robigus had a higher ground cover during spring and summer and intercepted more radiation (PAR) than the lesser competitive Hereward, thus indicating that a more extensive leaf cover was causing Robigus to be more competitive. This conclusion is supported by the work of Verschwele and Niemann (1994) who demonstrated that cultivars with high radiation interception decreased the growth of *A. myosuroides*. In other experiments, Cussans (2009) showed that the tall cultivar Maris Widgeon (*c.* 100 cm) reduced *A. myosuroides* head numbers by 16%, compared with the shorter Hereward (*c.* 80 cm). Moss (1985c) demonstrated that the more competitive winter wheat cultivar of the two tested reduced *A. myosuroides* heads by 25% and the more competitive winter barley reduced heads by 55%. In both crops, the more competitive cultivar tended to be taller than the less competitive one. Additionally, in the barley, the more competitive cultivar was a 6-row type compared with the less competitive 2-row barley.

Discussion

The data analysed were from 52 field experiments that examined the effects of crop management on the control of *A. myosuroides* in winter cereals. The meta-analyses, supported by the category (2) and (3) data clearly show that adopting cultural control measures can reduce *A. myosuroides* infestations. The greatest effects were from changing the rotation to plant a spring cereal and the use of the mouldboard plough, instead of non-inversion tillage. These two reduced populations by an average of 88% and 69% respectively. The next most effective approach was to delay autumn sowing (until the end of October/November), which could reduce populations by up to 50%. Increasing crop seed rate was also effective, but the maximum reduction in head numbers of about 40% was only achieved by substantial increases in wheat crop density, from 100 to 350 plants m^{-2}. Growing more competitive cultivars was the least effective

Table 4 Comparisons of the influence of winter wheat cultivars on the numbers of *Alopecurus myosuroides* heads m^{-2}

		Percentage reduction in *A. myosuroides* heads m^{-2} when comparing…		
Data source	Number of cultivars tested	Most competitive and the mean of all cvs	Most and least competitive cvs	Robigus and Hereward*
Cussans (2009)	3	8	16	
Masstock (2008)	3	12	21	21
Masstock (2009)	19	10	19	9
Newton (2007) Expt 1	3	45	61	61
Newton (2007) Expt 2	10	36	52	52
Moss (1985c) Expt 1	2		22	
Moss (1985c) Expt 2	2		32	
Moss (1985c) Expt 3	2		20	
Mean		22.2	30.4 (33.8†)	35.8

Data are the percentage reductions in head numbers achieved by the more competitive cultivars.
*Data are the percentage reduction in *A. myosuroides* heads in Robigus (one of the most competitive wheat cultivars) compared with the number of heads in Hereward (one of the least competitive wheat cultivars).
†Mean of the five experiments with three or more cultivars.

option, reducing head numbers by 22–30% depending on the basis for the comparison. These results demonstrate the benefit of a range of cultural measures for the control of *A. myosuroides* and quantify the levels of weed control that can be achieved in the field. However, there are two key concerns that have to be acknowledged: (i) many of the cultural measures reviewed resulted in highly variable responses, and (ii) there are considerable practical and economic limitations to their successful implementation.

The responses to the different cultural practices varied very considerably in ways that were often not predictable. Even when significant mean responses were detected, the benefits in terms of percentage weed control varied greatly. For example, although mouldboard ploughing reduced *A. myosuroides* populations by an average of 69%, it could cause an 82% increase, or reduce populations by more than 95%. This variability is likely to be due to the multitude of factors affecting weed populations at the individual field level. These include the infestation level and past cultivation history affecting the depth distribution of weed seeds in the soil, the design, type and efficiency of operation of the cultivation equipment used, the soil structure and moisture, and the weather conditions both before and after cultivation. The relative amount of old seed in the soil seedbank compared with the amount of new, recently shed, seed on the soil surface is particularly important where mouldboard ploughing is practised. Soil inversion greatly changes the seed distribution of both old and new seeds in the soil, and this affects subsequent weed populations, as only *A. myosuroides* seeds within about 5 cm of the soil surface are capable of producing seedlings that can emerge successfully (Naylor, 1970). There were similar levels of variability in the sowing date and crop density data sets, as can be seen by the size of the confidence limits in Figs 1 and 2. This high level of variability is not unexpected and will come as no surprise to farmers and agronomists.

The response to delayed sowing is likely to be particularly influenced by weather conditions. The dormancy of *A. myosuroides* seeds is affected by climatic conditions during seed maturation, with hot dry conditions reducing innate dormancy (Swain *et al.*, 2006). However, subsequent germination is reliant on adequate autumn rainfall. Although relevant meteorological data were not available in the analysed experiments, it seems reasonable to conclude that delayed sowing has its major benefit in damp autumns, which encourage early germination of *A. myosuroides* seeds after the cereal harvest (July–September). These weed seedlings can then be destroyed prior to drilling the autumn-sown crop. In dry autumns, most *A. myosuroides* seeds will not germinate prior to sowing, and seedlings are more likely to emerge after the crop has been sown, which is typically in September or October in the UK. This conclusion is supported by the modelling work of Colbach *et al.* (2005) that predicts that delaying cultivations until mid-October will reduce populations (in France), but this response will only arise if September has appreciable rainfall.

Delaying sowing until the spring had a major impact on *A. myosuroides* populations, reducing them by a mean 88% compared with the population present in a September-sown crop in the same experiment. However, this conclusion is based on only five field trials and needs further validation. Krücken (1976) in Germany reported survey results that showed that where over 80% of the land was in winter cereals, *A. myosuroides* was present on 64% of fields, where 30–80% was in winter cereals, 35–42% of fields were infested, but with <30% of the area in winter cereals, this weed was not a problem. As *A. myosuroides* is so closely associated with winter cereal growing, replacing autumn-sown with spring-sown crops should reduce infestation levels. The systems experiments reported by Chauvel *et al.* (2009) also show that 'rotations with an alternation of spring and autumn crops were the most effective solution against black-grass'. So, more diverse rotations, including spring crops, are very valuable tools to decrease *A. myosuroides* populations, as was suggested by Ling and Price (1930) more than 80 years ago, but the lower profitability of spring crops deters many farmers from this approach (Pardo *et al.*, 2010).

Using more competitive cultivars seemed to have the lowest benefit but, assuming no other negative attributes associated with the chosen cultivar (e.g. lower yield, quality or greater disease susceptibility), could be an attractive 'no cost' option. There are a range of reasons why some wheat cultivars are more competitive than others. Taller plants, more planophile leaves, greater tillering, higher growth rate, allelopathy and the overall size of plants prior to stem extension may all contribute to greater competitive ability (Verschwele & Niemann, 1994; Seavers & Wright, 1999; Hansen *et al.*, 2008; Hoad *et al.*, 2008; Zerner *et al.*, 2008; Bertholdson, 2011). How these interact to create a particularly competitive cultivar is not well understood, and more research is needed to clarify the issues. Critically, the competitive potential of new cultivars must be quantified prior to marketing (Beckie *et al.*, 2008), as the longevity of winter wheat varieties on the UK recommended list is short, typically <5 years (HGCA, 2012). Indeed, both the varieties studied most intensively for their relative competitive ability in the UK (Hereward – uncompetitive; Robigus – more competitive) are no longer recommended and thus of limited current practical relevance.

A further major conclusion of this review is that the levels of weed control achieved by cultural practices are inferior to the degree of control expected from herbicides. The mean reductions in *A. myosuroides* populations achieved by mouldboard ploughing, delayed sowing, high seed rates and more competitive cultivars varied from 22% to 88%, although control in individual experiments could be higher. For *A. myosuroides* to be registered as 'susceptible' ('S' on the herbicide label) to a new herbicide in the UK, the product has to achieve over 95% control in at least 10 field efficacy trials (Chemicals Regulation Directorate, 2010). The ranges for 'moderately susceptible' (MS) and 'moderately resistant' (MR) are 85–95% and 75–85% respectively, and the weed is termed 'resistant' ('R') to the product if <75% control is achieved. So, if cultural practices were assessed on the same basis as herbicides, *A. myosuroides* would be described as resistant ('R') to most of the cultural practices reviewed here! So it is perhaps not surprising that farmers and their advisors have preferred to use herbicides to control their weeds. Not only is control lower and more variable, but the management complexity of adopting cultural practices is much greater than for the relatively simple application of herbicides (Moss, 2010).

Costs of cultural practices, either direct financial costs or costs in terms of management time, are also often higher than for herbicide applications. The importance of these 'costs' depends on the individual farm management approaches and on the scale of the weed problem on the individual farm. For example, mouldboard ploughing, in comparison with a non-inversion disc/tine system, will typically add £25–40 ha^{-1} (€30–47 ha^{-1}) and increasing seed rates, £15–25 ha^{-1} (€18–30 ha^{-1}), to variable costs (Nix, 2013). In addition, mouldboard ploughing tends to be slow and has perceived negative impacts on carbon sequestration and mitigation of greenhouse gas emissions. Later autumn sowing may reduce crop yields and increase the risk of poor establishment, or failure to establish a crop at all. In comparison, a graminicide mixture used for control of *A. myosuroides* would typically cost £30–40 ha^{-1} (€35–47 ha^{-1}) in the UK, although many farmers will use herbicide programmes costing £65–85 (€75–100 ha^{-1}) or more (Nix, 2013).

The key to increasing farmer acceptance of cultural control methods is to show that, if several cultural practices are combined, they will have an additive effect. This was the main conclusion of similar studies in Canada: '….the effectiveness and consistency of these non-herbicide weed management practices greatly increases when three or more of these practices are simultaneously employed' (Blackshaw *et al.*, 2008a). In France and Canada, there have been several studies on the effectiveness of combining cultural control measures (Blackshaw *et al.*, 2008b; Chauvel *et al.*, 2009; Chikowo *et al.*, 2009), but the amount of such research is limited, because of the complexity and cost, so the wider conclusions are somewhat speculative. Organic growers also adopt a range of cultural practices to manage weeds (Neuhoff *et al.*, 2004), but it is difficult to extrapolate from organic to conventional farming practices because of differences in fertility and rotations.

The main message from this study is that cultural control methods can help reduce the pressure on herbicides resulting from reduced availability, lack of new modes of action and increasing resistance. In the UK, there is growing awareness amongst farmers that herbicides should not be considered the sole means of weed control. To prevent populations of *A. myosuroides* reaching unsustainable levels in an era when less reliance can be placed on herbicides, farmers will need to change their cropping practices to:

- include mouldboard ploughing in their rotational tillage plans,
- include spring crops in the rotation,
- delay sowing winter cereals until at least mid-October especially in their worst infested fields,
- increase winter wheat seed rates and not be tempted to reduce rates below 200 seeds m^{-2},
- grow more competitive winter cereal cultivars.

More than 50 years ago, Salisbury (1961) in his book 'Weeds and Aliens' finishes his chapter on herbicides by saying that, 'established agricultural practices are the first line of defence against many evils (*weeds!*), whilst herbicides should be regarded as a supplement to, not a substitute for, good husbandry'. This message is, perhaps, even more relevant today than it was 50 years ago. Cultural measures will not eliminate the need for herbicides, and overall success is likely to vary between fields and seasons, but they can reduce the pressure on herbicide performance. Decisions on weed control by farmers and their advisors are made at an individual field level, on individual farms. Information on the mean effects of different cultural measures is useful in showing their potential, but is difficult to relate directly to an individual field. Farmers are unlikely to replace herbicides with non-chemical methods unless they have greater confidence in the likely outcomes at the individual field level. Means of achieving this should be a priority in future research.

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Appendix 1 Data used in the meta-analysis of the effects of cultivations on *A. myosuroides* plants m^{-2}

Source	Experiment	Untransformed means			Mean and SED of Log_{10}-transformed values			
		Tine/Disc	Plough	Direct drill	Tine/Disc	Plough	Direct drill	SED*
Moss (1985a)	Expt 1	128		261	2.101		2.411	0.0484
Moss (1979)		426	74	543	3.60	2.78	3.73	0.2400
Moss (1981)		347	13	412	2.45	1.07	2.30	0.2620
Pollard *et al.* (1982)	Buckland	78	4	177	1.892	0.541	2.237	0.1718
	Compton	68	23	77	1.691	1.342	1.743	0.1438
Cook *et al.* (2006, annual expts)	Box 2002	54	17	102	1.535	1.062	1.713	0.1297
	Box 2003	59	52	262	1.624	1.464	2.271	0.1854
	Box 2004	457	207	553	2.510	2.233	2.537	0.1413
	RRES 2002	1000	823	716	2.635	2.515	2.511	0.1257
	RRES 2003	42	8	115	1.376	0.828	1.891	0.1399
	RRES 2004	3229	557	2841	3.390	2.624	3.362	0.0852
	TAG 2002	723	329	821	2.824	2.409	2.803	0.1151
	TAG 2003	583	85	465	2.150	1.688	1.867	0.3056
	TAG 2004	12.5	15	16	1.015	1.156	1.080	0.1420
	Vel 2003	1842	653	1511	3.130	2.686	3.171	0.1661
	Vel 2004	58	11.5	13	1.277	0.709	0.795	0.1576
Cook *et al.* (2006, long-term expts)	Box	283	14		1.928	1.058		0.1425
	Vel	424	98		2.605	1.969		0.0557
Moss (2001, unpubl. obs.)		683	208		2.784	2.261		0.1093
Froud-Williams *et al.* (1983)	Northfield	10.1	0.8	6.1	0.83	0.29	0.77	0.139
	Compton Beauchamp		0.1	1.9		0.07	0.58	0.071
Moss (1987a)		138		147	2.137		2.165	0.0551
Moss (1985b)	Expt 1		81	285		1.868	2.446	0.1448
	Expt 2		36	209		1.552	2.310	0.0836
Moss (1980)	Freeland	22	40	39	1.317	1.576	1.573	0.1369

*SED compares all three cultivation methods except in experiments where only two methods are included.

Appendix 2 Data used in the meta-analysis for the effect of autumn sowing date on *A. myosuroides* plants and heads m^{-2}

Source	Experiment	Sowing date	Days from 1 August	Untransformed means		Mean and SED of Log_{10}-transformed values			
				Plants m^{-2}	Heads m^{-2}	Plants m^{-2}	SED	Heads m^{-2}	SED
Tatnell (2001)		25 September	56	150	704	2.009	0.1184	2.787	0.1184
		15 November	107	20	170	1.202	0.1184	1.99	0.1184
Moss (1985a)	Expt 2	11 September	42	98	140	1.99	0.0476	2.143	0.0338
		02 October	63	168	540	2.222	0.0476	2.726	0.0338
		24 October	85	134	406	2.121	0.0476	2.587	0.0338
	Expt 3	15 September	46	283	485	2.451	0.0283	2.679	0.0404
		02 October	63	264	446	2.421	0.0283	2.648	0.0404
		24 October	85	205	129	2.309	0.0283	2.105	0.0404
	Expt 4	25 September	56	486	1276	2.683	0.0144	3.076	0.0518
		24 October	85	510	1011	2.705	0.0144	2.993	0.0518
	Expt 5	29 September	60	553	602	2.73	0.027	2.768	0.0238
		24 October	85	452	471	2.642	0.027	2.659	0.0238

Appendix 2 (Continued)

Source	Experiment	Sowing date	Days from 1 August	Untransformed means		Mean and SED of Log_{10}-transformed values			
				Plants m^{-2}	Heads m^{-2}	Plants m^{-2}	SED	Heads m^{-2}	SED
Cook *et al.* (2006)	Box 2002	30 September	61	85	440	1.739	0.0947	2.542	0.0859
		07 January	160	12	439	1.024	0.0947	2.516	0.0859
	2003	16 September	47	143	24	1.892	0.1354	0.982	0.1756
		14 October	75	49	12	1.486	0.1354	0.726	0.1756
	2004	01 November	93	421	74	2.498	0.1032	1.649	0.146
		15 December	137	331	233	2.311	0.1032	2.181	0.146
	RRES 2002	26 September	57	1643	77	3.179	0.0918	1.785	0.1274
		10 December	132	100	45	1.945	0.0918	1.567	0.1274
	2003	19 September	50	46	278	1.459	0.1022	2.276	0.1598
		17 October	78	39	204	1.06	0.1022	1.825	0.1598
	2004	29 September	60	3331	474	3.368	0.0622	2.527	0.1636
		14 December	136	834	443	2.788	0.0622	2.369	0.1636
	TAG 2002	16 September	47	547	256	2.585	0.0841	2.334	0.1081
		10 October	71	622	43	2.723	0.0841	1.323	0.1081
	2003	13 September	44	273	647	1.723	0.2232	2.651	0.1164
		14 October	75	447	514	2.093	0.2232	2.532	0.1164
	2004	07 October	68	19	14	1.217	0.1038	0.773	0.1438
		17 November	109	10	0.2	0.951	0.1038	0.057	0.1438
	Vel 2003	30 September	61	1615		3.093	0.1213		
		28 October	89	985		2.828	0.1213		
	2004	10 October	71	58	801	1.515	0.1151	2.86	0.0888
		25 November	117	2	273	0.391	0.1151	2.363	0.0888
Moss and Hull (2012)	2001	21 September	52	860	1130	2.915	0.0863	3.041	0.0833
		16 January	169	330	941	2.476	0.0863	2.954	0.0833
	2005	27 September	58	6101		3.758	0.0517		
		17 November	109	1152		3.045	0.0517		
	2010	19 September	50	660	829	2.798	0.0441	2.911	0.0323
		19 October	80	555	834	2.733	0.0441	2.912	0.0323

Appendix 3 Data included in meta-analysis of the effect of crop density on the number of *A. myosuroides* plants and heads m^{-2}

Source	Experiment	Untransformed data			Mean and SED of Log_{10}-transformed values			
		Crop density plants m^{-2}	*A. myosuroides* plants m^{-2}	*A. myosuroides* heads m^{-2}	*A. myosuroides* plants m^{-2}	SED plants	*A. myosuroides* heads m^{-2}	SED heads
Moss (1985c)	Expt 3 early	134	532	669	2.714	0.0467	2.815	0.0412
		220	557	585	2.729	0.0467	2.756	0.0412
		277	571	551	2.748	0.0467	2.733	0.0412
	Expt 3 late	121	475	558	2.66	0.0467	2.743	0.0412
		182	440	478	2.631	0.0467	2.676	0.0412
		228	441	378	2.635	0.0467	2.558	0.0412
	Expt 4	174	537	667	2.727	0.0529	2.816	0.0599
		258	490	613	2.688	0.0529	2.787	0.0599
		374	462	481	2.658	0.0529	2.68	0.0599
	Expt 5	120	410	2605	2.607	0.1254	3.385	0.1413
		316	538	1020	2.697	0.1254	3.000	0.1413
		508	543	1195	2.692	0.1254	3.073	0.1413
Moss (2001, unpubl. obs.)		84	1238	1296	3.072	0.0863	3.095	0.0833
		228	860	1130	2.915	0.0863	3.041	0.0833
Moss (2010, unpubl. obs.)	Sown late	112	603	953	2.78	0.0624	2.977	0.0456
		231	506	716	2.685	0.0624	2.846	0.0456

Appendix 4 Data used in the comparison of the effects of crop density on *A. myosuroides* heads m^{-2} (data not included in meta-analyses)

Data source	Experiment	Wheat plants m^{-2}	*A. myosuroides* heads m^{-2}	% Reduction over lowest crop density
Farmers Weekly magazine (2003)	Masstock 2003	134*	922	
		201*	431	53.3
Newton *et al.* (2007)	Masstock 2005	134*	153	
		268*	114	25.5
Newton *et al.* (2007)	Masstock 2006	117*	473	
		235*	370	21.8
Masstock (2010)	Masstock 2007	117*	571	
		235*	470	17.7
Masstock (2010)	Masstock 2008	117*	385	
		181*	322	16.4
		235*	273	29.1
Cussans (2009)	Rothamsted 2003	90	85	
		180	61.5	27.6
		360	31.3	63.2
Magri (2011, pers. comm.)	Syngenta 2010	134*		
		201*		7†
		268*		14†
Norman (2009, pers. comm.)	Velcourt 2009	67*	68	
		235*	36	46.6
Moss (2008, unpubl. obs.)	Woburn 2008	67	653	
		201	593	9.2
Moss (2011, unpubl. obs.)	Woburn 2011	122	507	
		228	465	8.3
		324	432	14.8

*Wheat plant numbers estimated from seed rate sown (seed rate and 0.67).
†*A. myosuroides* head counts presented as percentage reductions over lowest crop density.

Appendix 5 Details of experiments studying the effects of wheat cultivars on *A. myosuroides* heads m^{-2}

Data sources	Experiment	Wheat densities (plants m^{-2})	Number of cultivars	Data
Newton *et al.* (2007)	Masstock 2005	124, 268	3 Winter wheat	Heads m^{-2}
	Masstock 2006	117, 235	10 Winter wheat	Heads m^{-2}
Masstock (2010)	Masstock 2008	117, 181, 235	3 Winter wheat	% Control of heads
	Masstock 2009	–	19 Winter wheat	% Control of heads
Cussans (2009)	Rothamsted 2003	90, 180, 360	3 Winter wheat	Heads m^{-2}
Moss (1985c)	Expt 1	272, 220	2 Winter wheat 2 winter barley	Heads m^{-2}
	Expt 2	245, 292	2 Winter wheat 2 winter barley	Heads m^{-2}
	Expt 3	127, 201, 235	2 Winter wheat	Heads m^{-2}