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Estimating the farm-level economic costs of spring cropping to manage *Alopecurus myosuroides* (black-grass) in UK agriculture

K. Ahodo[1], D. Oglethorpe[2], H. L. Hicks[3] and R. P. Freckleton[1*]

[1] Department of Animal and Plant Sciences, The University of Sheffield, Western Bank, S10 2TN, Sheffield, UK.

[2] Cranfield School of Management, Cranfield University, UK, MK43 0AL

[3] School of Animal, Rural & Environmental Sciences, Nottingham Trent University, Nottingham, UK, NG1 4FQ

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Abstract

Crop rotation is a non-chemical strategy adopted by farmers to manage weeds. However not all crops in a rotation are equally profitable. Thus, there is potentially a trade-off between the costs and benefits of this strategy. The objective of the current study is to quantify this trade-off for the rotational control of an important weed (*Alopecurus myosuroides*). Data from 745 farms were used to parameterize a farm-level mixed-integer goal-programming model of the economics of spring cropping for weed control in UK agriculture. On average the short-term loss of profit from spring cropping is greater than the benefits in terms of reduced herbicide usage and yield increases. These costs are greater when weed densities are low, so that spring cropping is an expensive strategy in the early stages of an infestation. However, there is a great

* **Author for correspondence:** R. P. Freckleton, E-mail: r.freckleton@sheffield.ac.uk

deal of farm-to-farm variation: factors such as soil type and farm size are important and the current study highlights that economic modelling at the farm level is important in enabling farmers to make informed decisions. In general, however, if spring cropping is to be a successful strategy then the benefits to farmers will be in terms of long-term reductions in weed densities, but this will be at the expense of short-term profitability.

Keywords: *Weed management, black-grass, spring cropping, UK arable farming systems, goal programming*

Introduction

Pests and weeds are a threat to sustainable farming systems because serious infestations can reduce the yield potential of arable crops (Sells, 1995; Lucas, 2011). Also, they are a threat to sustainability because modern agriculture is reliant on chemicals to control pests. Integrated Pest Management (IPM) promotes the use of pest management strategies that rely heavily on non-chemical pest management strategies or cultural practices and thus it prescribes minimum or sometimes no use of chemicals, prevents the use of chemicals with certain active ingredients or substances (Hillocks, 2012; Ahuja *et al*., 2015; Lechenet *et al*., 2017; Bottrell and Schoenly, 2018).

As part of IPM, Integrated Weed Management (IWM) promotes sustainable management of weeds (Chikowo *et al*., 2009; Pardo *et al*., 2010), if possible through the use of cultural practices to control weeds. Ideally IWM should not incur penalties in terms of productivity and total economic performance (Chikowo *et al*., 2009). Realistically, however, IWM strategies may incur costs because of reductions in profit as farmers switch between crops that vary in profitability. These costs may be offset if there is less reliance on expensive chemicals.

Black-grass (*Alopecurus myosuroides* Huds.) is the most important annual grass weed in the UK and Europe (Moss *et al*., 2007; Lutman *et al*., 2013; Keshtkar *et al*., 2015). It is very competitive and has the ability to produce large quantities of seeds. In autumn-sown arable crops, *A. myosuroides* can cause substantial yield reductions (Lutman *et al*., 2013; Keshtkar *et al*., 2015). The high frequency of autumn sown crops in the UK has contributed to an increase in *A. myosuroides* infestations (HGCA, 2008; Keshtkar *et al*., 2015). As with most pests, the control of *A. myosuroides* has been primarily through the use of chemicals. However, it has evolved resistance to a number of herbicides (Moss *et al*., 2007). There is therefore a need to find alternative crop husbandry to reduce *A. myosuroides* infestation as well as to re-balance the financial consequences of yield loss through *A. myosuroides* infestation.

Integrated Weed Management (IWM) strategies for *A. myosuroides* control include tillage practices (e.g. ploughing), cultural practices (e.g. delayed sowing) and crop rotation (with spring cropping) (Colbach *et al*., 2000; Moss and Hull, 2012; Lutman *et al*., 2013; HGCA, 2014a; Bayer, 2015). Crop rotation with spring cropping is beneficial in several respects for the sustainability of agricultural systems (Schönhart *et al*., 2011; HGCA, 2014a). In terms of weed control it is effective in reducing *A. myosuroides* population: reductions of 78–96% in populations are reported from the use of spring crops (Moss and Hull, 2012; Lutman *et al*., 2013). This is because *A. myosuroides* germinates primarily in the autumn, with very few plants emerging in spring sown crops (Chauvel *et al*., 2005; Colbach *et al*., 2010). Despite these advantages, a major drawback of spring crops is that they yield lower economic returns. For example, in 2014, the Gross Margin for winter wheat and spring barley were £833/ha and £647/ha, respectively, whereas their respective herbicide costs were £70/ha and £48/ha (Nix, 2014). Switching from winter wheat to spring barley to control *A. myosuroides* reduces Gross Margin by £183/ha whereas herbicide cost reduces by only £22/ha. Thus following a winter crop with a spring crop is likely to reduce herbicide input and cost but with a bigger reduction in revenue due to lower yields associated with spring crops (Pardo *et al*., 2010; Moss and Hull, 2012; Bayer, 2015).

Research on the effect of spring cropping on *A. myosuroides* control normally focuses on yield and weed populations and based on field experiments, but ignores economic costs. Some studies (Pardo *et al*., 2010; Beltran *et al*., 2012) have used dynamic farm-modelling approaches to investigate non-chemical weed management strategies under IWM. However, none of these studies estimated the cost of *A. myosuroides* control to farmers at a national scale using cultural control methods. The national scale picture is also important because recent years have seen reductions in the area of wheat grown in the UK as farmers adopt alternative crops to manage *A. myosuroides* (Hicks *et al*., 2018).

The objective of the current study is thus to estimate the economic cost/benefit of crop plans, which includes a winter wheat–spring crop rotation as control measure for *A. myosuroides*. A model that is appropriate for predicting the economically optimal cropping for a given weed infestation is presented. Farm data from across the UK are used to parameterize the model and predict the range of variation in outcomes, as well as to forecast the national impacts of wide-scale adoption of this strategy to manage *A. myosuroides*. The analysis presented in the current study is most relevant to understanding the short-term economic consequences of rotational management of *A. myosuroides* with spring crops. The results presented in the current study are novel because there has been no previous analysis of the economics of controlling *A. myosuroides* using rotational management at farm or national scales.

Materials and methods

Farming scenario

The current study considers a typical arable rotation containing four crops: winter wheat (*Triticum aestivum* L.), spring barley (*Hordeum vulgare* L.), spring beans (*Vicia faba* L.) and winter oilseed rape (*Brassica napus* L.). Although other crops such as winter barley and spring wheat are important in UK arable farming, these four crops represent the rotational options used to control *A. myosuroides* (H. L. Hicks, personal communication). The study was built on the previous models of Annetts & Audsley (2002), Rounsevell *et al.* (2003) and Cooke *et al.* (2013).

A set of sequential and non-sequential farm operations are carried out on each crop during the farm year. The farm season is divided into 26 two-week periods during which farm operations such as sowing or harvest occur (see Fig. A1 in Appendix A for the operation types and sources of information). The workable hours available to the farm to carry out each operation in each period depend on the soil type and rainfall pattern at the farm location. Also, the rate at which earth moving operations such as ploughing are carried out depends on the soil type, whilst the work rate of operations such as planting and combine harvesting depend on the seed amount and crop yield respectively.

The work rates of both sequential and non-sequential operations depend on the size of machines owned by the farm (see Table A1 in Appendix A for machine types used for the study and sources of information). The dominant soil type (in addition to the previous crop grown) at the farm determines the fertilizer amounts applied to each crop [recommended fertilizer amounts to soil type taken from Defra (2010)].

In the current study, the crop rotation is a 4-year crop cycle. Farms practising crop rotation decide the number of hectares of land allocated to a crop as well as the deciding following crops. The choice of crop will depend on the objective of the farmer, and other factors such as soil type, revenue, weather and risk (Dury *et al.*, 2012).

Two crop plan options (summarized in Fig. 1) are considered in the current study, one unconstrained winter wheat–spring crop rotation (Option 1) and another rotation constrained to include winter wheat followed by a spring crop (Option 2). In Option 1 there are four fields available and farmers may grow any of the four crops: winter wheat (WWHT), spring barley (SBAR), spring beans (SBEA) and winter oilseed rape (WOSR). In terms of crop sequence or succession it is assumed that each crop can be grown on any of the fields A, B, C and D (as shown by the arrows in Fig. 1(a)) and there are no constraints imposed on the winter wheat–spring crop rotation.

Option 2 implements rotational management of *A. myosuroides* (as shown in Fig. 1(b)) in which a winter wheat–spring barley or spring beans sequence is adopted. The main difference between Option 1 and 2 is that under Option 2 any land from which WWHT has been harvested is constrained to be sown with either spring barley or spring beans in the next season (i.e. winter wheat is always followed by a spring crop).

Insert Fig. 1 here

Modelling black-grass infestation

A. myosuroides population infestation is modelled empirically through contrasting scenarios of winter wheat yield reductions under different infestations (low, medium, high and very high: see Queenborough *et al*., 2011 for definitions of densities). This was done for simplicity in order to make it possible to contrast the economic consequences of employing rotational control at different stages of infestation.

The mixed-integer weighted goal programming (MIGWP) model

The MIWGP model allows weights and goal targets to be set to optimize farming goals by selecting optimum crop plan and machines/labour numbers. The model was set up to select four crops: winter wheat, spring barley, spring beans and winter oilseed rape. The model assumes that there is always one farmer (integer) in addition to the labour numbers selected by the model (assumed to be permanent workforce) and thus makes the model a mixed-integer.

The decision variables are the crop types and each crop plan selected by the model comes with it, machine and labour numbers.

The risk minimization goal was based on the principles of the minimization of total absolute deviation (MOTAD) approach (Hazell, 1971) and hence the standard deviation of Gross Margin was used as a measure of risk. Although, a typical MOTAD model could have been applied, with the primary focus on profit maximization and some consideration to risk, the MIWGP model, which incorporates a risk goal was found to serve the same purpose as a MOTAD model, hence fit for purpose.

The MIWGP model minimizes total deviations in profit and risk goal targets (Eqn 1) subject to profit maximization (Eqn 2) and risk minimization (Eqn 3) and a set of constraints under the model constraint section below, where Dev is the total deviation in profit and risk goal targets, d_1^- is the negative deviation from the profit maximization goal target, d_2^+ is the positive deviation from the risk minimization goal target, and u_1 and v_2 are the relative weights attached to the negative deviation in profit and positive deviation in risk goal targets respectively. All other model notations are summarized in Table 1. Summations are taken over the periods and operations for each crop, which vary from crop to crop. The algebraic expressions shown by Eqns (2) – (6) are adapted from expressions used by Annetts and Audsley (2002), Rounsevell *et al*. (2003) and Cooke *et al*. (2013).

Minimize $Dev = u_1 d_1^- + v_2 d_2^+$ (1)

Subject to:

Goal 1: Profit maximization

$$G_{profit} = \sum_c E_c a_c - \sum_c \sum_j \sum_k C_{cjk} y_{cjk} - \sum_m C_m n_m + u_1 d_1^- = T_1 \qquad (2)$$

$$a_c = \sum_k y_{c1k} \qquad (3)$$

Goal 2: Risk minimization

$$G_{risk} = \sum_c a_c \sigma_c - v_2 d_2^+ = T_2 \qquad (4)$$

Insert Table 1 here

Model constraints

Resource constraints

This constraint ensures that the amount of a resource needed to carry out an operation on a crop does not exceed the amount of the resource available. The resource type considered is the number of workable hours available in a period:

$$\sum_{c}\sum_{j} s_{cjkm} y_{cjk} \leq L_{mkw} n_m \quad \forall m, k, w \tag{5}$$

Sequential and non-sequential operation constraints

The sequential operation constraint ensures that an operation is not performed before its preceding operation and that the area of the successor operation cannot exceed the area of the preceding operation. For example, a crop has to be planted before it can be harvested and that the area of crop harvested cannot exceed the area of crop planted. The constraint can be expressed as shown in Eqn (6). For non-sequential operations, total area of each operation carried out in a period cannot exceed the total crop area.

$$\sum_{k \leq K} y_{cjk} \leq \sum_{k \leq K} y_{c(j-1)k} \quad \forall\, c, j > 1, k \tag{6}$$

Winter wheat–spring crop sequence constraint

This constraint ensures a spring crop following winter wheat. If the area of winter wheat = a_1, area of spring barley = a_2 and area of spring beans = a_3, the winter wheat–spring barley sequence constraint can be stated as in Eqn (7) and under a scenario of ensuring winter wheat–spring beans sequence, a_2 is replaced with a_3.

$$a_1 - a_2 \leq 0 \tag{7}$$

Total cropping area constraint

The sum of areas of all crops is less than or equal to the total area cropped. This means that the total land area cropped by a farmer cannot exceed the total cropping area available to the farmer, i.e.:

$$\sum_{c} a_c \leq \text{Total cropping area} \tag{8}$$

Model validation

The model was implemented using the R environment (R Core Team, 2015), and the mixed-integer weighted goal programming model was solved using the Rglpk package (https://cran.r-project.org/web/packages/Rglpk/Rglpk.pdf). The MIWGP model was validated using prediction validation (McCarl and Spreen, 1997) and 2009-2013 Farm Business Survey (FBS) data for 281 lowland arable farms in England and Wales. The Farm Business Survey (https://www.gov.uk/government/collections/farm-business-survey) gives information about information on the financial, physical and environmental performance of farm businesses in England and Wales. Some of the data collected in the FBS are crop yield, crop areas, margins and costs. Crop yields, farm area, soil types and rainfall were used as data inputs (see Table A2 in Appendix A for descriptive statistics of these data). The soil type determined the fertilizer amounts for each crop, and both the annual rainfall and soil data determined the workable hours using the land indicator type (LTI) function (Tillett and Audsley, 1987):

$$LTI = 20.6X^2 - 89X + 212 \tag{9}$$

where $X = (1.257 - 0.257SoilType)Rainfall + 0.762(SoilType - 1)$. The soil type is based on indices from 0.5 to 2.5 at an interval of 0.25, representing light to heavy soil. The LT1 were used in a series of equations to determine workable hours for different periods. In Defra (2010), fertilizer amount recommended for crops were linked to soil type and this was incorporated into the MIWGP model.

The results generated by the model as part of the validation were compared with corresponding observed FBS data using statistical measures of association, specifically: Pearson correlation (r), Spearman rank correlation (ρ), coefficient of determination (R^2), Nash-Sutcliffe's model efficiency (NSE), Willmott's index of agreement (WIA) and coefficient of residual mass (CRM) (see equations of statistical measures of association in Appendix A). Each of the statistical measures of association has its strengths and weaknesses. The inclusion of multiple statistical measures permits a more thorough characterization of the predictive abilities of the models.

Economic evaluation

The economic evaluation was based on estimates of crop Gross Margin, defined as output plus subsidy less fertilizer, seed, *A. myosuroides* herbicide and sundry costs. The output estimates were based on crop yields and prices, whereas the subsidy was based on Single Farm Payment values, and the sundry costs were obtained from Nix (2014). Fertilizer cost estimates were based on recommended amounts in Defra (2010), determined by soil type. Seed amounts were obtained from Toosey (1988). *A. myosuroides* control costs were determined by chemical costs only (see Table A3 in Appendix A).

The operations costs (primarily fuel) were functions of work rates for machines and fuel price. The equations for estimating the work rates were obtained from the farmR model (Cooke *et al.*, 2103) and Chamen and Audsley (1993). Estimation of the operations cost took into consideration timeliness penalties. The fixed cost estimates were based on annual machinery cost (depreciation and repair costs) and annual labour cost (see Table A1 under Appendix A for machine types selected for the current study). Owing to lack of data on machine numbers for each of the farms selected and used for the current study, the total fixed cost estimate for each farm was based on the optimal machine/labour numbers estimated by the model.

Model data, calibration and model runs

Data from 745 farms in the 2013/14 Farm Business Survey (FBS) were used to parameterize the model. Crop yield, price, arable area, soil type and rainfall were used as input (see Table A4 in Appendix A for descriptive statistics). Farms at altitudes < 300 m, 300 – 600 m and > 600m with arable area of greater than or equal to 40 ha (maximum area = 1931 ha) were selected. Soil type data were based on dominant soil types obtained for FBS defined counties in which farms are located (Soilscapes, 2016) whereas the rainfall data were based on average rainfall for FBS defined regions in which farms are located (Met Office, 2016). The soil type and rainfall data were used to estimate the workable hours for each farm using the LTI function in Tillett and Audsley (1987). To model the impact of *A. myosuroides* on winter wheat yield, yield losses under four different *A. myosuroides* infestation levels were considered (see Table A5 in Appendix A).

The model was run with the highest weight (weight = 1) on the profit maximization goal and because a weighted goal programming model minimizes the deviation from a goal target, the profit maximization goal target was set very high (£800 000) to accommodate profit levels of all farms. Based on the assumption that arable farmers are profit maximizers, but with some concern about income deviation (risk) levels, the weight for the risk minimization goal was set relatively very small (weight = 0.1 and risk target set at £22 000 with possible over-achievement of goal target).

The model was first run for each of the 745 farms to generate crop plans similar to Option 1, under each level of *A. myosuroides* infestation (one level of infestation at a time), without enforcing the winter wheat–spring crop sequence constraint (Eqn 7). The model was run again for each farm by first imposing only the mandatory winter wheat–spring barley sequence constraint (Option 2) under each level of infestation. The process was repeated by imposing only the winter wheat–spring beans constraint (also Option 2) under each level of infestation.

Aggregation of model results

To estimate the net cost of adopting spring cropping as a control strategy for *A. myosuroides*, model results were aggregated across farms. It was acknowledged that there may be biases associated with aggregation with respect to linear programming approaches and also due to variability in farm classes (Buckwell and Hazell, 1972; Önal and McCarl, 1989). However, the current approach gave a fair estimate of the impact of spring cropping as *A. myosuroides* control strategy on farm revenue in the UK arable farming sector.

To estimate the aggregate cost/benefit, the differences in optimum profits for Options 1 and 2 were estimated and aggregated as either the cost (loss of profit) or benefit (increase in profit) of *A. myosuroides* control with either spring barley or spring beans. For example, in order to estimate the aggregate cost with respect to winter wheat–spring barley rotation under each level of infestation, the difference between profits for Option 1 and Option 2 were estimated for each farm after which they were summed across the 745 farms. To reduce possible aggregation bias and bring the aggregate estimate as close as possible to the UK level, each farm estimate was weighted using the sample weight assigned to each farm in the FBS. For each spring cropping sequence and under each level of infestation, the aggregate cost was estimated as shown in Eqn (10).

$$Aggregate\ Cost = \sum_{z=1}^{F} OP2_z wt_z - \sum_{z=1}^{F} OP1_z wt_z \qquad (10)$$

Results

Model Validation

Estimates of *r*, *ρ* and R^2 showed positive associations between model results and observed data (Table 2). The Spearman and Pearson's correlation estimates for crop area, fertilizer amount, cost and revenue predictions were statistically significant ($P < 0.01$).

The *NSE* and *WIA* estimates showed various degrees of association between predicted and observed data and also reflect the predictive ability of the model with respect to the model estimates. The positive *CRM* estimates showed under predictions by the model. Also, based on the *NSE* and R^2 estimates, it can be said that the model predicted crop areas and fertilizer amount relatively better than farm costs and revenues. This may due to the fact that certain factors influencing these costs and revenues on farms may not have been captured in the model. Notwithstanding, predictions of costs and revenues made by the model can be said to be acceptable or reasonable based on the correlation estimates, and fit the objective of the current study.

The *NSE*, *WIA* and *CRM* estimates thus reflect the limitation associated with model prediction. This limitation can be overcome on a farm-by-farm basis through inclusion of detailed individual farm data, or by aggregating predictions across many farms to average across this variation resulting from these unknown costs. The methodology adopted in the current study concentrated mainly on the latter approach.

Insert Table 2 here

The cost of black-grass control with spring barley

The aggregate costs of controlling *A. myosuroides* with spring barley under scenarios of low and very high infestations were approximately £82/ha and £10/ha respectively (Table 3). Implementing a winter wheat–spring barley rotation after a low *A. myosuroides* infestation reduced profit by 25.30% (from £326/ha to £244/ha) and under very high infestation, profit reduced by 7.49% (from £133/ha to £123/ha) (see Table 3).

At low *A. myosuroides* infestation, implementing Option 2 also reduced the MOTAD estimated risk by 5.17% (from £225/ha to £214/ha), whereas under very high infestations risk reduced negligibly (0.23%, ~£198/ha in both cases). The reduction was mainly due to lower income deviation estimates associated with spring barley as well as winter OSR, which was selected in addition to the winter wheat–spring barley rotation. The results also showed that controlling *A. myosuroides* with spring cropping could reduce farm risk due to lower deviation income through deviation in yield associated with spring crops. However, under a scenario of very high infestation the reduction may be negligible due to the fact that spring cropping did not result in a bigger reduction in profit. The lower levels of profit observed under scenarios of *A. myosuroides* infestations were mainly due to reductions in winter wheat yield due to *A. myosuroides* infestation.

In terms of costs, all variable cost components reduced under rotational management. For example, under low *A. myosuroides* infestation, nitrogen (N) fertilizer and herbicide costs reduced by 9.63% (from £188/ha to £170/ha)) and 15.63% (from £177/ha to £150/ha) respectively. Under very high infestation, N fertilizer and *A. myosuroides* control costs reduced by 3.73% (from £169ha to £162/ha) whereas *A. myosuroides* control (herbicide) cost reduced by 6.45% (from £147/ha to £138/ha). The reduction in N fertilizer and herbicide costs was due to lower N fertilizer and chemical control costs associated with spring barley. Lower reductions in herbicide costs under very high infestation occurred because there was little difference in the crop plan (relative to Option 1) when winter wheat–spring barley sequence constraint was imposed.

Operations and fixed costs on the other hand increased by 7.10% (from £335/ha to £359/ha) and 1.79% (from £444/ha to £452/ha), respectively, under low infestation. Under very high infestation, operations cost increased by 2.61% (from £370/ha to £380/ha) and fixed cost increased by 1.15% (from £449/ha to £454/ha) respectively. The increase in operations cost was because, with the implementation of the winter wheat–spring barley rotation, some land was allocated to winter oilseed rape (OSR) or spring beans. Both spring beans and winter OSR had slower work rate with respect to combine harvesting and as a result relatively more time was spent on the field harvesting, leading to increased operation costs. Also the harvesting periods of winter wheat and spring barley overlapped, meaning that more machines/labour were needed in order to perform harvesting within the optimal periods and as a result led to increase in fixed cost.

Scaling up to the UK farming community as a whole, it was estimated that controlling *A. myosuroides* with a crop plan using spring barley under a scenario of low *A. myosuroides* infestation could cost UK arable farming about £286 million whereas under a scenario of very high *A. myosuroides* infestation, adoption of winter wheat–spring barley rotation as *A. myosuroides* control strategy could cost UK arable farming about £35 million.

Insert Table 3 here

The cost of black-grass control with spring beans

Table 4 shows the predicted aggregate costs of controlling *A. myosuroides* with spring beans. This strategy resulted in 57.51% reduction in profit (from £326/ha to £139/ha) under low *A. myosuroides* infestation (see Table 4). Under very high weed infestation, profit reduced by 18.94% (from £133/ha to £108/ha).

With low *A. myosuroides* infestation, MOTAD estimated risk also reduced by 6.81% (from £225/ha to £210/ha) but increased by 2.92% (from £198/ha to £204/ha) under very high infestation. The increase in risk under very high infestation was due to the crop combinations selected by the model after the winter wheat–spring beans rotation constraint was imposed. The Gross Margin estimate associated with spring beans was relatively lower than that of spring barley and as a result, with imposition of winter wheat-spring beans sequence, more land was allocated to spring barley which was associated with relatively high risk and hence the increase in the MOTAD risk.

In terms of costs, variable cost components reduced under Option 2 compared to Option 1. For example, under low infestation, N fertilizer cost reduced by 25.61% (from £188/ha to £140/ha), whereas *A. myosuroides* herbicide cost reduced by 32.02% (from £177/ha to £120/ha). Under very high infestation, N fertilizer reduced by 15.29% (from £169/ha to £143/ha) and chemical control cost reduced by 21.42% (from £147/ha to £116/ha). The greater reduction in N fertilizer and *A. myosuroides* herbicide costs was because spring beans had no N fertilizer requirement, and because other crops (spring barley and winter OSR) selected as part of the rotation had lower N fertilizer requirements and *A. myosuroides* chemical costs than winter wheat.

Under very high weed infestation, there was little change in the crop plan (under Option 1) when winter wheat–spring beans was imposed, hence lower reduction in herbicide costs. Farm operations and fixed costs increased by 25.16% (from £335/ha to £419/ha) and 5.55% (from £444/ha to £469/ha) respectively under low infestation. Under very high infestation, operations cost increased by 14.01% (from £370/ha to £422/ha) and fixed cost increased by 6.38% (from £448/ha to £477/ha). Comparatively, larger increases in operations and fixed costs (than under spring barley) were due to the selection of some amount of winter OSR in the rotation. In terms of harvesting work rate, spring beans and winter OSR had slower work rate, leading to greater operations costs. Moreover, the harvesting periods of winter wheat, spring beans and spring barley overlapped meaning that more machines/labour were needed to perform the operations, leading to higher fixed cost and hence bigger reduction in profit.

At a national scale, it was estimated that adopting a winter wheat–spring beans rotation as *A. myosuroides* control measure under a scenario of low *A. myosuroides* infestation could cost UK arable farming about £650 million (£187/ha) whereas under a scenario of very high infestation, the strategy could cost UK arable farming about £87 million (£25/ha).

Insert Table 4 here

The cost/benefit of black-grass control at individual farm level

The previous analyses have been aggregated across 745 farms for which FBS data were available. Within this sample there was enormous variability of course, and in this section the precise answer to the question of whether rotational control is economically costly will depend on local circumstances is highlighted.

The results of two farms labelled Farm 1 and Farm 2 were used for the illustration (see Table 5). These cases were used to show that, although at the aggregate level, using winter wheat–spring crop rotation as *A. myosuroides* control measure could cost the arable sector, at the individual farm level, there could be either reductions (costs) or increase (benefits or gains) in farm revenue depending on the location of the farm. The dominant soil type for Farm 1 was a light soil whereas that of Farm 2 was a heavy soil. In terms of rainfall, Farm 1 was located in an area of moderate rainfall and Farm 2 was located in an area of high rainfall. In terms of the control of *A. myosuroides*, these two cases are significant: *A. myosuroides* is generally thought to be a more significant problem on heavy land with higher rainfall than on light drier land (Metcalfe *et al*., 2018).

The differences in soil type are important in terms of workability: Farm 1 had relatively more time available to perform farm operations whereas Farm 2 was restricted. This reflected in the cropping pattern of Farms 1 and 2 (see Table 5). Under Option 1 for Farm 1, about 97% (127ha) of the land (131ha) was allocated to winter wheat, which was the most profitable crop whereas under Farm 2 land was allocated to all the four crops in order to maximize profit, with about 45% (119ha) of farm area (267ha) allocated to winter wheat.

Under Option 2 for Farm 1, to be able to adopt a winter wheat–spring barley sequence as *A. myosuroides* control measure and maximize profit, 57 ha of winter wheat was cropped (70 ha or 55% less of 127 ha) however, under Farm 2, 104 ha (15 ha or 13% less of 119 ha) was cropped. There was no drastic reduction in the area of winter wheat, which was the most profitable crop under Farm 2, and this coupled with the selection of all the other crops, associated with lower variable costs resulted in the increase in Gross Margin (profit) instead of reduction observed under Farm 1.

On Farm 1, using winter wheat–spring barley rotation as *A. myosuroides* control reduced profit by £7583 (a cost) whereas under Farm 2 profit increased by £783 (a gain or benefit) however, risk increased under Farm 2. The increase in risk may be due to the fact that the estimate of risk was linked to Gross Margin estimates and hence increase in Gross Margin was likely to be associated with increase in risk. A farmer whose primary aim is to maximize profit with little consideration to risk is likely to accommodate high risk so as to maximize profit. In terms of herbicide cost, for Farm 1, it reduced by 28% (from £23 023 to £16 570) whereas under Farm 2, it reduced by about 4% (from £34 901 to £33 582). This was as a result of the allocation of land to all four crops under Farm 2 and hence contributed to the smaller reduction in *A. myosuroides* control cost. The reductions in herbicide cost shows the possibility of gains in terms of cost savings by controlling *A. myosuroides* with spring cropping however, in the case of Farm 1, the reduction was not big enough to offset the reduction in profit.

Insert Table 5 here

Discussion

The results presented in the current study indicate that, in the short-term, the costs of rotational control of *A. myosuroides* depend on the rotation selected as well as the initial density of the weed. The results suggest that it will cost UK arable farming more by adopting winter wheat–

spring beans rotation than adopting winter wheat–spring barley rotation however, under a scenario of very high infestation, winter wheat–spring beans rotation could result in lower profit loss than under low *A. myosuroides* infestation. A winter wheat–spring barley rotation could cost UK arable farming between £35 million (high infestations; £10/ha) and £286 million (low infestations; £82/ha) whereas controlling *A. myosuroides* with winter wheat–spring beans could cost UK arable farmers between £87 million (high infestations; £25/ha) and £650 million (low infestations; £187/ha) respectively.

There are potentially long-term benefits, and the economic picture may change if a longer planning horizon is used. This is because, if successful, spring crops reduce the densities of weeds in subsequent crops. The results represent a snapshot of the impacts of alternative management strategies in the short- to medium-term.

The figures presented are averaged across a large number of farms, which masks site-to-site variation. Although there was an average reduction in profit from the use of rotational control, it has been shown that there could be reductions in variable costs and in some cases reduction in farm risk. Consequently on an individual farm basis, there are potentially economic gains from spring cropping as a strategy for controlling *A. myosuroides,* depending on the location of farm and the area of land available to the farmer. Given such variability, modelling tools are potentially valuable for evaluating the viability of alternative rotational strategies on a farm-by-farm basis.

Investigation of the effect of spring cropping on *A. myosuroides* has typically been based on field experiments (Chauvel *et al*., 2001; Moss and Hull, 2012; Keshtkar *et al*., 2015). However, such experiments are expensive and time consuming and do not consider economic outcomes. Models, such as the one presented in the current study, allow rapid exploration of a range of alternatives. Although some studies have applied mathematical models to investigate weed management strategies in IWM (Swinton and King, 1994; Pannell *et al*., 2004; Pardo *et* *al*., 2010; Beltran *et al*., 2012), none of these studies have evaluated the costs of adopting a non-chemical weed control measure across a national scale.

Lower profits from spring crops make arable farmers reluctant to adopt non-chemical weed management strategy under IWM (Chikowo *et al*., 2009). Controlling *A. myosuroides* with spring cropping reduced overall profits owing to lower profits associated with spring crops as well as winter OSR (Nix, 2014). Also, the reduction in profit was partly due to the increase in operations and fixed costs due to the crop combination, and the implication is that farmers need to choose cropping plans aimed at reducing labour and machinery costs through efficient labour and machinery planning (Barnard and Nix, 1973). Thus if arable farmers in UK were to adopt winter wheat–spring crop rotations to control *A. myosuroides*, the strategy needs to be combined with efficient timing or planning of operations and machinery/labour use especially in periods in which labour requirements are high.

In some cases controlling *A. myosuroides* with spring cropping can be economically beneficial. The current study has illustrated using two hypothetical examples that this depends on factors such as soil type, prevailing rainfall pattern and the amount of cropping land available to the farm. Although in the case of Farm 1, the selection of crops defied the 3 crop rule under the greening policy, it was found that with the imposition of greening constraints, the differences in the model estimates were found to be marginal. Notwithstanding, the results showed that, for some arable farmers, controlling *A. myosuroides* with spring crops has the potential to be profitable due to the associated lower variable costs and the high cost of chemical control associated with winter crops (ADAS, 2007). With the inability of *A. myosuroides* to develop resistance to non-chemical control strategies, drawing on the benefits of non-chemical control measures such as crop sequences or rotations, in addition to ploughing and delayed sowing could make *A. myosuroides* control very effective (Moss and Lutman, 2013; HGCA, 2014b). This can reduce chemical inputs, which in turn could improve profitability and benefit the environment.

The analysis presented in the current study is most relevant to understanding the short-term economic consequences of rotational management of *A. myosuroides* with spring crops. In terms of long-term benefit, successful spring crops reduce the densities of weeds in subsequent crops and the mechanism for this is reduced seed input to the soil resulting from lower weed densities. This is why spring cropping has been recommended as a method to control *A. myosuroides* (Moss and Hull, 2012). However the net impacts of spring cropping on *A. myosuroides* can be very variable across sites (Freckleton *et al*., 2018). At the farm level, an evaluation of the long-term economics of spring cropping requires that this variability is accounted for, and models for population dynamics of the weed are integrated with whole farm economic models. The model presented in the current study is a first step in this direction.

It is potentially important to view the impact of this modelling in a policy context. The eradication or mitigation of *A. myosuroides* is a major challenge and in terms of food security and environmental protection, its management provides positive public goods. The provision of positive externalities from agriculture have generally been encouraged through the adoption of the provider gets principle (Hanley and Oglethorpe, 1999; Hanley *et al*., 1998). Under a provider gets principle, the policy maker rewards the policy adopter. Thus the aggregate per hectare costs of *A. myosuroides* management provide us with an indication of the need for possible policy payments to incentivize adoption of the system needed to generate those positive externalities. The overall cost of £82/ha suggested by the model for imposition of the spring barley rotation would represent such a possible payment level if farmers were to adopt spring cropping after incidence of zero or low *A. myosuroides* infestation. However, with relatively lower loss of profit under a scenario of very high *A. myosuroides* infestations on winter crop fields, farmers may be better off switching to spring cropping and such payments to incentivize adoption may not be required.

The overall effect of controlling *A. myosuroides* with spring crops resulted in a reduction in profit, which could affect the adoption of such non-chemical strategies by arable farmers. However, with EU Sustainable Use of Pesticides Directive requiring arable farmers to give priority to non-chemical methods of plant protection (HGCA, 2014b), research using linear programming based optimization approaches to come up with optimal profit estimates of different spring cropping strategies to control *A. myosuroides* could encourage farmers to adopt such non-chemical control measures as part of a package of weed control strategies.

Conclusions

The investigation of spring cropping as *A. myosuroides* control measure using a static mixed-integer weighted goal programming model showed that at the aggregate level, controlling *A. myosuroides* with winter wheat–spring crop rotation could reduce farm revenues in UK arable farming. At the individual farm level, there could benefits dependent on the farm's situations. The current study thus gives insight into how the adoption of weed management strategies can impact on farming goals and the need for possible payment schemes to incentivize adoption.

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Ethical Standards: Not applicable

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Table 1. Model notation

Notation	Unit	Explanation
C		Crop type
J		Operation type
K		Time period
K		Set of periods in which operations can be carried out. K = 26
M		Machine type
W		Workability type
Z		Farm, $z = 1, \ldots, F$ (F = total number of farms)
a_c	*ha*	Total area of crop *c* (It is equal to the sum of sum of the area of first operation (*j*=1) carried out on crop *c* in period *k*, y_{c1k})
C_{cjk}	*£/ha*	Cost of operation *j* carried on crop *c* in period *k*)
C_m	*£/machine*	Fixed cost (annual machinery and annual labour costs) of machine type *m*
d_1^-		Negative deviation from the profit maximization goal target
d_2^+		Positive deviation from the risk minimization goal target
Dev		Total deviation to be minimized from goal targets
E_c	*£/ha*	Expected Gross Margin for crop *c*
G_{profit}	*£*	Profit maximization goal
G_{risk}	*£*	Risk minimization goal
L_{mkw}	*h*	Workable hours available in period *k* to carry out operation with workability type *w* using machine type *m*
n_m		Number of machine of type *m*
$OP1_z, OP2_z$	*£*	Profits (cost or risk) of farm *z* for choosing Option 1 or Option 2 crop plans respectively
S_{cjkm}	*h/ha*	Work rate of operation *j* carried out on crop *c* in period *k* using machine type *m*
T_1, T_2	*£*	T_1 = profit goal target, T_2 = risk goal target
u_1		Relative weight attached to negative deviation from profit goal target
v_2		Relative weight attached to positive deviation from risk goal target
wt_z		Sampling weight attached to the *z*th farm
y_{cjk}	*ha*	Area of operation *j* carried on crop *c* in period *k*. With respect to sequential operations constraint, it is equal to the area of the successor operation
$y_{c(y-1)k}$	*ha*	Area of the predecessor operation $(y-1)$ carried on crop *c* in period *k*
σ_c	*£*	Standard deviation in income for crop *c*

Table 2. Model validation results of the comparison between predicted and observed crop areas, fertilizer amounts and farm revenues/costs.

Measure	Crop Area	Fertilizer amount	Fuel Cost	Seed Cost	Fertilizer Cost	Labour Cost	Fixed Cost	Gross Margin	Profit
r	0.94 ($P < 0.01$)	0.90 ($P < 0.01$)	0.79 ($P < 0.01$)	0.49 ($P < 0.01$)	0.86 ($P < 0.01$)	0.33 ($P < 0.01$)	0.73 ($P < 0.01$)	0.71 ($P < 0.01$)	0.49 ($P < 0.01$)
ρ	0.88 ($P < 0.01$)	0.74 ($P < 0.01$)	0.63 ($P < 0.01$)	0.74 ($P < 0.01$)	0.79 ($P < 0.01$)	0.44 ($P < 0.01$)	0.66 ($P < 0.01$)	0.72 ($P < 0.01$)	0.51 ($P < 0.01$)
R^2	0.89	0.80	0.61	0.24	0.74	0.12	0.53	0.51	0.24
NSE	0.89	0.76	0.11	0.19	0.74	0.01	0.26	0.20	-0.03
WIA	0.97	0.94	0.39	0.58	0.92	0.51	0.76	0.56	0.40
CRM	0.07	0.04	0.70	0.14	0.02	0.23	0.39	0.56	1.22

Crop area is the total crop areas of 281 farms predicted by the model. Fertilizer amount is the total nitrogen (N), phosphorous (P) and potassium (K) fertilizer amounts of 281 farms predicted by the model. The observed data were for 281 farms used to validate the model. r = Pearson correlation coefficient; ρ = Spearman correlation coefficient; R^2 = Coefficient of determination (estimated by squaring r); *NSE* = Nash-Sutcliffe's model efficiency; *WIA* = Willmott's index of agreement and *CRM* = Coefficient of residual mass.

Table 3. Aggregate revenues/costs (£) of controlling black-grass with winter wheat–spring barley rotation under four levels of black-grass infestation. These costs are expressed on a per hectare basis. R1–R13 represent the rows in the Table. The numbers in parentheses represent the differences in Option 1 and Option 2 profits. See Tables B1 and B2 under Appendix B for the mean and standard deviation estimates of the results.

			Zero / Low Infestation		Medium Infestation		High Infestation		Very High Infestation	
Cost / Revenue			Option 1	Option 2	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2
Output	R1	Yield × Price	1561	1435	1523	1416	1425	1363	1326	1305
Output + Subsidy	R2	R1+Subsidy	1811	1685	1773	1666	1675	1613	1576	1555
N Fertilizer Cost	R3		188	170	186	169	179	167	169	162
P Fertilizer Cost	R4		68	65	68	65	67	65	65	64
K Fertilizer Cost	R5		61	58	60	57	59	57	57	56
Seed Cost	R6		85	82	84	81	83	81	81	80
Black-grass Herbicide Cost	R7		177	150	174	148	163	145	147	138
Sundry Cost	R8		128	108	126	107	118	104	106	99
Variable Cost	R9	R3+R4+R5+ R6+R7+R8	706	631	697	628	669	618	625	599
Gross Margin	R10	R2-R9	1105	1054	1076	1038	1006	995	952	957
Cost of Farm Operations	R11		335	359	338	360	350	367	370	380
Gross Profit	R12	R10-R11	770	695	737	677	656	628	582	577
Fixed Cost	R13		444	452	443	452	443	452	449	454
Profit		R12-R13	326	244 **(-82)**	295	226 **(-69)**	213	176 **(-37)**	133	123 **(-10)**
MOTAD Risk		Deviation in income	225	214	221	211	209	204	198	198

N, nitrogen; P, phosphorus; K, potassium; MOTAD, minimization of total absolute deviation

Table 4. Aggregate revenues/costs (£) of controlling black-grass with winter wheat–spring beans rotation under four levels of black-grass infestation. These costs are expressed on a per hectare basis. R1–R13 represent the rows in the Table. The numbers in parentheses represent the differences in Option 1 and Option 2 profits. See Tables B1 and B3 under Appendix B for the mean and standard deviation estimates of the results.

			Zero / Low Infestation		Medium Infestation		High Infestation		Very High Infestation	
Cost / Revenue			Option 1	Option 2	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2
Output	R1	Yield × Price	1561	1317	1523	1312	1425	1301	1326	1291
Output + Subsidy	R2	R1+Subsidy	1811	1568	1773	1562	1675	1551	1576	1541
N Fertilizer Cost	R3		188	140	186	140	179	142	169	143
P Fertilizer Cost	R4		68	61	68	61	67	61	65	61
K Fertilizer Cost	R5		61	52	60	52	59	52	57	52
Seed Cost	R6		85	81	84	80	83	79	81	78
Black-grass Herbicide Cost	R7		177	120	174	120	163	118	147	116
Sundry Cost	R8		128	87	126	86	118	85	106	83
Variable Cost	R9	R3+R4+R5+ R6+R7+R8	706	541	697	540	669	537	625	534
Gross Margin	R10	R2-R9	1105	1026	1076	1021	1006	1014	952	1007
Cost of Farm Operations	R11		335	419	338	420	350	421	370	422
Gross Profit	R12	R10-R11	770	607	737	602	656	593	582	585
Fixed Cost	R13		444	469	443	469	443	473	449	477
Profit		R12-R13	326	139	295	133	213	120	133	108
				(-187)		**(-162)**		**(-93)**		**(-25)**
MOTAD Risk		Deviation in income	225	210	221	209	209	206	198	204

N, nitrogen; P, phosphorus; K, potassium; MOTAD, minimization of total absolute deviation

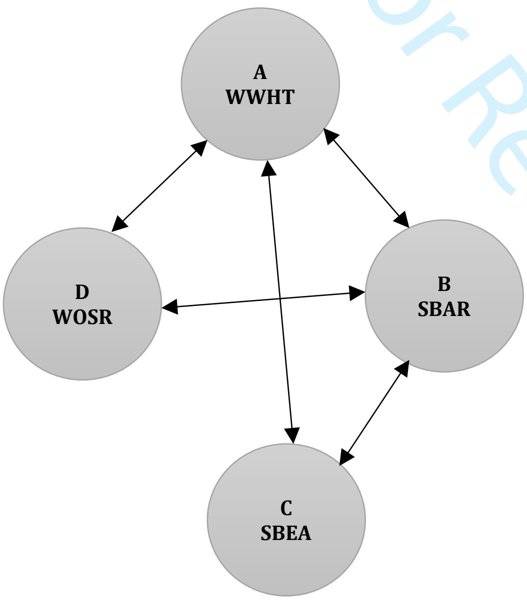
Table 5. Revenues/costs estimates of controlling black-grass with winter wheat–spring barley rotation for low level of black-grass infestations. R1–R13 represent the rows in the Table. The numbers in parentheses are the difference between Option 1 and Option 2 profits.

Revenue/ Cost Components (and Risk)	Row	Explanation	Unit	Farm 1		Farm 2	
				Option 1	Option 2	Option 1	Option 2
Output	R1	Yield × Price	£	154 957	138 320	290 531	289 899
Output + Subsidy	R2	R1+Subsidy	£	182 074	165 416	345 800	345 168
N Fertilizer Cost	R3		£	13 250	9610	37 733	36 162
P Fertilizer Cost	R4		£	7784	7034	14 499	14 329
K Fertilizer Cost	R5		£	7004	6323	12 627	12 464
Seed Cost	R6		£	9776	9633	18 416	18 488
Black-grass Herbicide Cost	R7		£	23 023	16 570	34 901	33 582
Sundry Cost	R8		£	16 640	11 747	25 281	24 269
Variable Cost	R9	R3+R4+R5+R6+R7+R8	£	77 476	60 917	143 457	139 295
Gross Margin	R10	R2-R9	£	104 597	104 499	202 343	205 873
Cost of Farm Operations	R11		£	33 140	32 560	82 226	83 683
Gross Profit	R12	R10-R11	£	71 455	72 023	120 109	122 182
Fixed Cost	R13		£	31 426	39 577	108 151	109 440
Profit	R14	R12-R13	£	40 029	32 446 **(-7 583)**	11 958	12 742 **(783)**
MOTAD Risk	R15	Deviation in income	£	22 000	21 759	45 713	46 018
Cropping							
Winter wheat			ha	127	57	119	104
Spring barley			ha	0	57	94	104
Spring beans			ha	4	17	13	18
Winter OSR			ha	0	0	41	40
Farm Information							
Farm area			ha	131		267	
Soil type				Light soil		Heavy soil	
Rainfall			mm	769		1294	

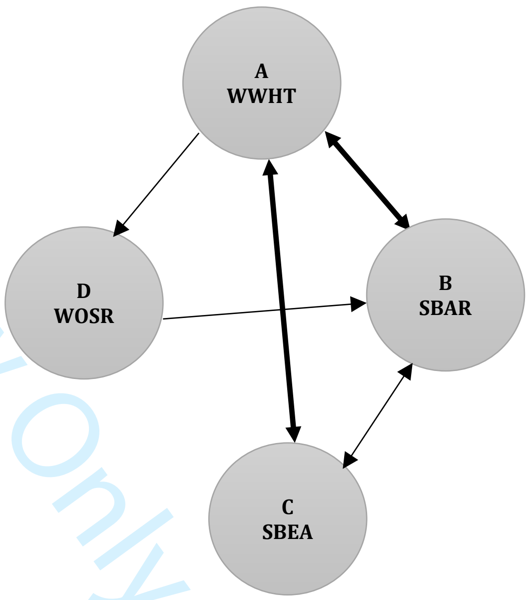
N, nitrogen; P, phosphorus; K, potassium; MOTAD, minimization of total absolute deviation

Fig. 1. Cropping plan scenarios. Option 1 is a scenario under which each crop can be grown on each of the four fields, A, B, C and D. Option 2 is a scenario under which mandatory WWHT (winter wheat)–SBAR (spring barley) or WWHT (winter wheat)–SBEA (spring beans) sequence is assumed (shown by thick arrow lines). WOSR = winter oilseed rape. The change in arrow between WWHT and WOSR means a WWHT field cannot be cropped with WOSR under Option 2. There is no arrow between WOSR and SBEA as a sequence or rotation between legumes and brassica crops are not encouraged due to possible disease build-up.

(a) Option 1



(b) Option 2



Appendices

Appendix A: Model data and evaluation of model parameters

PERIOD		WINTER WHEAT							
		FARM OPERATIONS							
		FE	FE (ns)	PO	PL	RO	SP	SP (ns)	CO
01 JAN - 15 JAN	p1						2		
15 JAN - 29 JAN	p2						2		
29 JAN - 11 FEB	p3						2		
12 FEB - 25 FEB	p4						2		
26 FEB - 11 MAR	p5						2	2	
12 MAR - 25 MAR	p6						2	2	
26 MAR - 08 APR	p7		2					2	
09 APR - 22 APR	p8		2					2	
23 APR - 06 MAY	p9							2	
07 MAY - 20 MAY	p10							2	
21 MAY - 03 JUN	p11								
04 JUN - 18 JUN	p12								
18 JUN - 01 JUL	p13								
01 JUL - 16 JUL	p14								
16 JUL - 29 JUL	p15								
30 JUL - 12 AUG	p16	1		1					
13 AUG - 26 AUG	p17	1		1					2
27 AUG - 09 SEP	p18	1		1					2
10 SEP - 23 SEP	p19	1		1	1	1			
24 SEP - 08 OCT	p20	1		1	1	1			
08 OCT - 21 OCT	p21	1		1	1	1			
22 OCT - 04 NOV	p22	1		1	1	1	1		
05 NOV - 18 NOV	p23	1		1	1	1	1		
19 NOV - 02 DEC	p24			1	1	1	1		
03 DEC - 16 DEC	p25			1	1	1	1		
16 DEC - 31 DEC	p26			1	1	1	1		

PERIOD		SPRING BARLEY							
		FARM OPERATIONS							
		FE	FE (ns)	PO	PL	RO	SP (ns)	CO	BA
01 JAN - 15 JAN	p1			2	2				
15 JAN - 29 JAN	p2			2	2				
29 JAN - 11 FEB	p3			2	2				
12 FEB - 25 FEB	p4			2	2				
26 FEB - 11 MAR	p5			2	2	2			
12 MAR - 25 MAR	p6			2	2	2			
26 MAR - 08 APR	p7		2		2	2	2		
09 APR - 22 APR	p8		2			2	2		
23 APR - 06 MAY	p9					2	2		
07 MAY - 20 MAY	p10						2		
21 MAY - 03 JUN	p11								
04 JUN - 18 JUN	p12								
18 JUN - 01 JUL	p13								
01 JUL - 16 JUL	p14								
16 JUL - 29 JUL	p15								
30 JUL - 12 AUG	p16	1							
13 AUG - 26 AUG	p17	1						2	2
27 AUG - 09 SEP	p18	1						2	2
10 SEP - 23 SEP	p19	1							2
24 SEP - 08 OCT	p20	1		1					
08 OCT - 21 OCT	p21	1		1					
22 OCT - 04 NOV	p22	1		1					
05 NOV - 18 NOV	p23	1		1					
19 NOV - 02 DEC	p24			1					
03 DEC - 16 DEC	p25			1					
16 DEC - 31 DEC	p26			1					

PERIOD		SPRING BEANS				
		FARM OPERATIONS				
		FE	PO	PL	SP (ns)	CO
01 JAN - 15 JAN	p1		2			
15 JAN - 29 JAN	p2		2			
29 JAN - 11 FEB	p3		2			
12 FEB - 25 FEB	p4		2	2		
26 FEB - 11 MAR	p5		2	2		
12 MAR - 25 MAR	p6		2	2		
26 MAR - 08 APR	p7			2		
09 APR - 22 APR	p8					
23 APR - 06 MAY	p9				2	
07 MAY - 20 MAY	p10				2	
21 MAY - 03 JUN	p11					
04 JUN - 18 JUN	p12				2	
18 JUN - 01 JUL	p13				2	
01 JUL - 16 JUL	p14					
16 JUL - 29 JUL	p15					
30 JUL - 12 AUG	p16	1				
13 AUG - 26 AUG	p17	1				
27 AUG - 09 SEP	p18	1				2
10 SEP - 23 SEP	p19	1				2
24 SEP - 08 OCT	p20	1	1			
08 OCT - 21 OCT	p21	1	1			
22 OCT - 04 NOV	p22	1	1			
05 NOV - 18 NOV	p23	1	1			
19 NOV - 02 DEC	p24		1			
03 DEC - 16 DEC	p25		1			
16 DEC - 31 DEC	p26		1			

PERIOD		WINTER OILSEED RAPE					
		FARM OPERATIONS					
		FE	FE (ns)	PO	PL	SP (ns)	CO
01 JAN - 15 JAN	p1						
15 JAN - 29 JAN	p2						
29 JAN - 11 FEB	p3						
12 FEB - 25 FEB	p4		2				
26 FEB - 11 MAR	p5		2			2	
12 MAR - 25 MAR	p6		2			2	
26 MAR - 08 APR	p7					2	
09 APR - 22 APR	p8		2			2	
23 APR - 06 MAY	p9		2				
07 MAY - 20 MAY	p10						
21 MAY - 03 JUN	p11						
04 JUN - 18 JUN	p12						
18 JUN - 01 JUL	p13						
01 JUL - 16 JUL	p14						
16 JUL - 29 JUL	p15						2
30 JUL - 12 AUG	p16	1		1	1		2
13 AUG - 26 AUG	p17	1		1	1		
27 AUG - 09 SEP	p18	1		1	1		
10 SEP - 23 SEP	p19	1		1	1		
24 SEP - 08 OCT	p20	1		1			
08 OCT - 21 OCT	p21	1		1		1	
22 OCT - 04 NOV	p22	1		1		1	
05 NOV - 18 NOV	p23	1		1		1	
19 NOV - 02 DEC	p24			1		1	
03 DEC - 16 DEC	p25			1			
16 DEC - 31 DEC	p26			1			

Note: The operations with (ns) are non-sequential operations. The shaded squares with 1's means operations carried out in year 1 of the crop season and the squares with 2's means operations carried in year 2 of the crop season. The squares with circles represent the optimal periods in which the operations can be carried out without timeliness penalties. FE = Spreading of phosphorous/potassium fertilizer, PO = Ploughing, PL = Planting, RO = Rolling, SP = Spraying, CO = Combine harvesting, BA = Baling, FE (ns) = Nitrogen fertilizer application (non-sequential), SP (ns) = Spraying (non-sequential).

Fig. A1. Sequential and non-sequential farm operations of winter wheat, spring barley, spring beans and winter oilseed rape. This was adapted from Cooke *et al*. (2013) who adapted the model of Annetts & Audsley (2003).

Table A1. Machine types and annual machinery/labour costs

Machine	Capacity	Cost (Price) (£)	Depreciation Rate (%)	Replace Year	Depreciation (£)	Repair Cost Rate (£)	Repair Cost (£)	Annual Cost (£)
Tractor	100kW	50 000	22	5	9559	12.05	6025	15 584
Power harrow	3-4m	16 000	14	4	3992	5	800	4792
Sprayer	1400 l	21 000	18	7	3168	6.8	1428	4596
Combine harvester	125kW	95 000	18	7	14 332	5.8	5510	19 842
Baler	--	14 000	11	7	2233	5.5	770	3003
Potato harvester	2 row tailed	80 000	18	7	12 069	6	4800	16 869
Sugar beet harvester	2 row tailed	70 000	18	7	10 560	5	3500	14 060
Annual labour cost	--	--	--	--	--	--	--	21 945

Note: Estimates were done taking into consideration an interest rate of 0.5% and inflation rate of 2.5%. Annual labour cost was obtained from Nix (2014). Prices/cost of machines were obtained from ABC (2014). Depreciation rates, replacement years and repair costs rates were taken from Cook *et al*. (2013).

Table A2. Summary crop yield, rainfall and farm area data for farms used in model validation

Variable	Unit	Mean	Standard deviation
Winter wheat yield	t/ha	8.0	1.18
Spring wheat yield	t/ha	5.9	0.87
Winter barley yield	t/ha	7.1	0.97
Spring barley yield	t/ha	5.8	0.85
Winter beans yield	t/ha	4.1	0.88
Spring beans yield	t/ha	3.7	0.74
Ware potatoes yield	t/ha	32.9	3.35
Winter OSR yield	t/ha	3.5	0.59
Sugar beet yield	t/ha	55.4	7.48
Winter wheat price	£/t	163.2	23.32
Spring wheat price	£/t	163.2	23.32
Winter barley price	£/t	151.0	27.48
Spring barley yield	£/t	151.0	27.48
Winter beans price	£/t	142.4	26.05
Spring beans price	£/t	142.4	26.05
Ware potatoes price	£/t	167.4	24.27
Winter OSR price	£/t	357.8	58.27
Sugar beet price	£/t	32.8	0.84
Farm area	ha	296.4	260.51
Rainfall	mm	834.8	210.06

OSR, oilseed rape

Table A3. Black-grass chemical control cost (£/ha)

Crop	Black-grass Control Cost (£/ha)
Winter wheat	178
Spring barley	84
Spring beans	96
Winter oilseed rape	112

Source: Black-Grass Resistance Initiative (BGRI) Project (http://bgri.info/) (H. L. Hicks, personal communication). The costs were average estimates based on all fields of a typical 240ha arable farm with a five-crop rotation.

Table A4. Summary rainfall, farm area, crop yield and price data for farms used for model runs under different farm plan options

Variable	Unit	Mean	Standard deviation
Annual Rainfall	mm	856.3	236.73
Area	ha	186.5	219.66
Winter wheat yield	t/ha	7.8	1.65
Spring barley yield	t/ha	5.7	1.05
Spring beans yield	t/ha	3.7	0.75
Winter OSR yield	t/ha	3.1	0.67
Winter wheat price	£/ha	163.1	22.41
Spring barley price	£/ha	150.7	16.33
Spring beans price	£/ha	220.8	17.17
Winter OSR price	£/ha	342.1	26.21

OSR, oilseed rape

Equations of statistical measures of association

$$r = \frac{\sum_{l=1}^{N}(P_l - P_{av})(O_l - O_{av})}{\sqrt{\sum_{l=1}^{N}(P_l - P_{av})^2}\sqrt{\sum_{l=1}^{N}(O_l - O_{av})^2}}, \quad R^2 = r^2$$

$$\rho = 1 - \frac{6 \times \sum_{l=1}^{N}(rank\ P_l - rank\ O_l)^2}{N(N^2 - 1)}$$

$$NSE = 1 - \left(\frac{\sum_{l=1}^{N}(P_l - O_l)^2}{\sum_{l=1}^{N}(O_l - O_{av})^2}\right)$$

$$WIA = 1 - \left(\frac{\sum_{l=1}^{N}(P_l - O_l)^2}{\sum_{l=1}^{N}(|P_l - O_{av}| + |O_l - O_{av}|)^2}\right)$$

$$CRM = \frac{(\sum_{l=1}^{N}O_l - \sum_{l=1}^{N}P_l)}{\sum_{i=1}^{N}O_l}$$

O_l is the observed data for the lth observation of the parameter of interest (e.g. crop areas), P_l is the model-predicted result of the lth observation of the parameter of interest (e.g. model predicted or generated crop areas), O_{av} and P_{av} are the means of the observed and predicted data respectively and N is the number of observations.

Estimation of yield losses due to the level of black-grass infestation

The estimates of yield losses due to black-grass infestation were averages across 10 fields based 2014 and 2015 winter wheat harvests based on a black-grass survey carried out on farms in England (The English counties in which farms were located are: Northamptonshire, Oxfordshire, Warwickshire and Yorkshire (Hicks *et al*., 2018). For each field, yield maps were overlaid with 20m×20m weed survey grid to relate wheat yield to weed density. For each field, mean yield across grid squares in each density state was estimated. To control for variation in yield between fields, the maximum mean yield from the five density states was selected as 100%, and percentage yield calculated for each density state relative to this. The data on yield loss shown in Table A5 were adopted due to inability to obtain a UK level data.

Table A5. Yield reduction of winter wheat at four different levels of black-grass infestation

Level of Infestation	Black-grass Density (Plants per 400 (20×20) m^2)	Reduction in Winter Wheat Yield (%)
No/low	1-160	0
Medium	161-450	3
High	451-1450	12
Very high	>1450	24

Appendix B: Descriptive statistics of study results

Table B1: Weighted mean and standard deviation estimates of model results for 745 farms under Option 1 crop plan

Model Estimates	Low infestation		Medium infestation		High infestation		Very high infestation	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Output	240 167	280 177	234 338	273 287	219 191	257 799	204 038	240 398
Output + Subsidy	278 646	322 910	272 815	316 064	257 669	300 685	242 516	283 355
N Fertilizer Cost	28 901	32 744	28 579	32 418	27 521	31 340	25 942	30 103
P Fertilizer Cost	10 485	11 828	10 428	11 768	10 251	11 588	9 976	11 375
K Fertilizer Cost	9 317	10 557	9 250	10 491	9 058	10 323	8 745	10 087
Seed Cost	13 013	14 687	12 946	14 614	12 758	14 438	12 445	14 195
Black-grass Herbicide Cost	27 262	30 913	26 752	30 392	25 131	28 835	22 627	26 870
Sundry Cost	19 709	22 329	19 342	21 955	18 158	20 815	16 345	19 381
Variable Cost	108 687	122 745	107 297	121 299	102 878	116 860	96 081	111 541
Gross Margin	169 959	202 687	165 518	197 549	154 792	187 617	146 435	176 316
Cost of Farm Operations	51 500	57 996	52 073	58 712	53 829	60 828	56 921	63 448
Gross Profit	118 458	148 178	113 446	142 223	100 961	129 863	89 514	115 997
Fixed Cost	68 306	77 640	68 087	77 376	68 166	78 696	69 009	78 916
Profit	50 152	79 556	45 359	74 002	32 795	61 463	20 505	49 098
MOTAD Risk	34 641	39 457	33 922	38 531	32 102	36 471	30 504	34 508

Sd, Standard deviation; N, nitrogen; P, phosphorus; K, potassium; MOTAD, minimization of total absolute deviation. The unit for all estimates are £.

Table B2. Weighted mean and standard deviation estimates of model results for 745 farms under Option 2 crop plan with mandatory winter wheat–spring barley rotation

Model Estimates	Low infestation		Medium infestation		High infestation		Very high infestation	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Output	220 813	259 998	217 877	256 381	209 675	246 977	200 811	236 222
Output + Subsidy	259 292	302 981	256 355	299 371	248 153	289 967	239 290	279 177
N Fertilizer Cost	26 117	29 945	26 008	29 878	25 642	29 215	24 974	28 700
P Fertilizer Cost	10 032	11 397	10 012	11 384	9 944	11 268	9 819	11 158
K Fertilizer Cost	8 870	10 146	8 841	10 132	8 749	10 017	8 584	9 853
Seed Cost	12 562	14 272	12 537	14 257	12 449	14 136	12 290	13 965
Black-grass Herbicide Cost	23 002	26 452	22 838	26 353	22 252	25 384	21 168	24 479
Sundry Cost	16 561	19 009	16 447	18 940	16 036	18 243	15 270	17 625
Variable Cost	97 144	111 117	96 683	110 821	95 072	108 031	92 104	105 528
Gross Margin	162 148	193 788	159 671	190 681	153 081	184 938	147 185	177 122
Cost of Farm Operations	55 157	61 325	55 449	61 475	56 466	63 134	58 409	65 089
Gross Profit	106 990	134 955	104 224	131 678	96 616	124 363	88 774	115 040
Fixed Cost	69 528	78 815	69 472	78 870	69 477	80 190	69 803	79 663
Profit	37 462	64 387	34 752	61 346	27 139	54 212	18 970	47 949
MOTAD Risk	32 850	37 569	32 472	37 065	31 433	35 735	30 433	34 486

Sd, Standard deviation; N, nitrogen; P, phosphorus; K, potassium; MOTAD, minimization of total absolute deviation. The unit for all estimates are £.

Table B3. Weighted mean and standard deviation estimates of model results for 745 farms under Option 2 crop plan with mandatory winter wheat–spring beans rotation

Model Estimates	Low infestation		Medium infestation		High infestation		Very high infestation	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Output	202 671	237 825	201 766	236 150	200 083	235 185	198 549	233 625
Output + Subsidy	241 150	280 741	240 245	279 086	238 561	278 093	237 027	276 491
N Fertilizer Cost	21 500	24 315	21 572	24 399	21 774	24 773	21 976	24 915
P Fertilizer Cost	9 422	10 652	9 418	10 648	9 405	10 628	9 393	10 623
K Fertilizer Cost	8 054	9 175	8 054	9 177	8 059	9 206	8 055	9 206
Seed Cost	12 414	14 091	12 365	14 032	12 214	13 759	12 070	13 671
Black-grass Herbicide Cost	18 533	20 856	18 431	20 723	18 083	20 080	17 780	19 900
Sundry Cost	13 360	14 990	13 288	14 893	13 036	14 422	12 823	14 294
Variable Cost	83 284	93 898	83 129	93 708	82 570	92 692	82 097	92 448
Gross Margin	157 867	188 566	157 116	187 109	155 990	187 413	154 930	186 208
Cost of Farm Operations	64 459	72 633	64 540	72 802	64 697	72 854	64 894	72 910
Gross Profit	93 404	119 178	92 575	117 461	91 295	118 049	90 036	117 052
Fixed Cost	72 094	80 847	72 093	80 672	72 821	83 640	73 413	84 108
Profit	21 311	50 629	20 482	49 336	18 474	47 649	16 623	47 311
MOTAD Risk	32 282	36 805	32 117	36 505	31 727	35 930	31 393	35 626

Sd, Standard deviation; N, nitrogen; P, phosphorus; K, potassium; MOTAD, minimization of total absolute deviation. The unit for all estimates are £.