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Using stochastic dynamic programming to support weed management decisions over a rotation

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Summary

This paper describes a model that predicts the impact of weed management on the population dynamics of arable weeds over a rotation, and presents the economic consequences. A stochastic dynamic programming optimisation is applied to the model to identify the management strategy which maximises gross margin over the rotation. The model and dynamic programme were developed for the weed management decision support system – 'Weed Manager'. Users can investigate the effect of management practices (crop, sowing time, weed control and cultivation practices) on their most important weeds over the rotation, or use the dynamic programme to evaluate the best theoretical weed management strategy. Examples of the output are given in this paper, along with discussion on their validation. Through this work, we demonstrate how biological models can; (i) be integrated into a decision framework and (ii) deliver valuable weed management guidance to users.

Keywords: population dynamics, decision support system

Introduction

Weed control in UK arable crops is an expensive necessity for farmers. The survey of pesticide usage in Great Britain in 2002 shows that, on average, 5.3 herbicide active ingredients were applied to every wheat crop (Garthwaite *et al*., 2002). Adequate weed control can often be achieved by tackling the problem as it occurs in the season of production. This is not necessarily the most cost effective approach and, as species become increasingly resistant to herbicides, it may not always be successful. Additionally, weed control in the current season may not give immediate financial reward, but could help avert uncontrollably high weed densities in subsequent years. Hence, a long term approach to weed control is wise.

Simulation models allow us to explore the complexities of weed management decisions that influence the impact of weeds on gross margins. However, due to the large number of possible strategies, it is particularly appropriate to use a decision algorithm to find the best theoretical solution. In this paper we describe a model developed to investigate weed control strategies over a rotation and an associated dynamic programme developed to optimise weed management.

Our model, which is similar to others (Holst *et al.,* 2007), is based on the life cycle model developed by Moss (1990) which estimates seed fecundity and survival. The soil is considered to have a deep and shallow layer, and the model tracks the changes in the seedbank in each layer. Seeds migrate between layers when cultivations are applied. Seedlings emerge from the shallow soil layer and are killed to variable degrees by weed control practices. Surviving plants produce seeds that are returned to the shallow layer. These two state-variables (shallow and deep seedbank) describe the change in the weed population through the rotation, as modified by a series of management parameters. Yield loss due to weeds is estimated in each season and the associated gross margin calculated. This allows the effect of control strategies to be assessed in terms of seedbank density and gross margin over the rotation. To allow for the large uncertainties present in the system (primarily from the estimate of initial seedbank size), the seedbank density is described by a probability distribution.

Population models have been integrated into decision frameworks (Holst *et al.*, 2007; Park *et al.*, 2003). Typically the methods used rely on treatment thresholds, and these have been subject to criticism (Park *et al.*, 2003). We applied the stochastic dynamic programming (SDP) method (Howard, 1960) to our model to find the management strategy that maximises future rewards. Dynamic programming was developed to solve problems that are essentially repeated decisions over time, and therefore is the appropriate method for this application. Additionally, dynamic programming gives optimal decisions in problems with moderately complex state and decision variables, whereas thresholds are suitable only for single (or very limited) choices. In this problem, the reward is made up of future gross margins, and the strategy considers sowing time, cultivation and herbicide control. Crop rotation could also have been included in the strategy, but as it is driven largely by considerations other than weed control, it is specified within the model.

The approach used here is based on work of Sells (1993, 1995) who modified the Moss (1990), Doyle *et al*. (1986) and Cousens *et al.* (1986) models for use in a SDP. Sells (1993, 1995) calculates the optimal strategy for controlling *Alopecurus myosuroides Huds* (black-grass) and *Avena fatua* L. (wild-oats). Because of the SDP memory requirements Sells had to simplify the model to a single soil layer. For the present system, two layers (shallow and deep) are needed to model the impact of alternative cultural practices on seed distribution in the soil. By using slightly fewer discrete classes to describe seed density than Sells, and given the increases in computing power available, a two-layer model was solved for up to two weed species in an acceptable time. The method used to handle larger numbers of species is discussed.

The model and SDP were developed as part of the Weed Manager decision support system (Tatnell *et al.*, 2006), which is designed to run on a personnel computer. Several research groups have developed decision support systems that advise on within season weed control (Berti *et al.*, 2003; Neeser *et al.*, 2004; Bennett *et al.*, 2003) but only recently has attention been paid to rotational weed management (see Holst *et al.*, 2007). Weed Manager is currently parameterised for 12 common annual weed species and was designed so that this 'rotational module' runs alongside a 'within season module' (Benjamin *et al.*, 2009) that estimates the yield losses caused to winter wheat in one growing season. Details of the model and decision processes are described below, along with examples of the output and a discussion on its validation.

The population dynamics model

Model structure

The starting point of the annual life cycle is taken, for convenience, shortly after harvest when the weed population is present only as seeds in the soil. The numbers of seeds (seeds m^{-2}) in the shallow and deep layers at the start of season *t* are denoted $N_s(t)$ and $N_d(t)$ respectively. The shallow layer is defined as the top 5 cm and the deep layer as between 5 and 25 cm, the latter being the average depth of ploughing in the UK.

When soil is cultivated, a proportion, *d*, of the seeds in the shallow layer is buried to the deep layer and a proportion, *u*, of the seeds in the deep layer is brought up to the shallow layer. A proportion, *g*, of the seeds in the shallow layer germinate (seedling establishment is possible only from shallow layer seeds). Following weed control, a proportion, θ, of seedlings die. The number of mature plants in season *t* is

$$N_\mu(t) = \left[N_s(t)(1-d) + N_d(t)u\right]g(1-\theta) \qquad (1)$$

The number of viable seeds produced by the mature plants is

$$S(t) = \frac{N_{\mu}(t)(1-h)v\beta}{1+\alpha N_{\mu}(t)} \tag{2}$$

where α is the reciprocal of the plant density which gives the maximum seed production per unit area, β is the number of seeds per plant, v is the proportion of seeds that are viable, h is the proportion of seeds lost by herbivory.

If m is the proportion of ungerminated seeds that die in the soil per season, then the number of viable seeds that persist in the shallow layer ($Q(t)$) during season t is

$$Q(t) = \left[N_s(t)(1-d) + N_d(t)u\right](1-g)(1-m) \tag{3}$$

Therefore the number of seeds in the shallow layer at the beginning of season $t+1$ is

$$N_s(t+1) = S(t) + Q(t) \tag{4}$$

There is no direct contribution of seed rain to the deep seed layer at the start of each season. Hence the number of seeds in the deep layer at the beginning of season $t+1$ is

$$N_d(t+1) = \left[N_s(t)d + N_d(t)(1-u)\right](1-m) \tag{5}$$

In the model, the kill of seedlings, θ, from mechanical and herbicide weed control measures is augmented by the loss of weed seedlings due to delayed drilling. This augmentation is calculated from the seasonal emergence patterns of the weed species (Mortimer, 1990). The proportion of kill due to delayed drilling is assumed to be the ratio of the number of seedlings that emerged before drilling to the total number of seedlings to emerge.

The start of seedling emergence is defined as the earliest possible seedbed preparation date for autumn-sown crops and the 1st August of the previous year for spring-sown crops. Seedling emergence ends 60 days after the sowing date.

The crop rotation and weed management strategy

Crop rotation is defined by the user. In the model, choice of crop affects weed populations through its planting date, the estimate of the weed free yield, Y_0, crop market value, M, and variable costs, V. The crops included are: winter and spring types of wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), oilseed rape (*Brassica napus ssp oleifera* (DC) Metzg.), and field beans (*Vicia faba* L.), spring peas (*Pisum sativum* L.), potatoes (*Solanum tuberosum* L.), sugarbeet (*Beta vulgaris* L.) and a ryegrass ley (exemplified by *Lolium multiflorum* Lam.).

The weed management strategy defines cultivation, sowing time and herbicide control. Cultivations affect the migration of seeds between the shallow and deep layers. Therefore the parameters d and u in Eqns 1, 3 and 5 are cultivation dependent. For simplicity, instead of modelling each type of seedbed cultivation tool, three classes of cultivation are considered: ploughing (d = 0.95, u = 0.35), non-inversion cultivation (d = 0.5, u = 0.1) or, in the potato crop only, rotary cultivation (d = 0.833, u = 0.167) (based on Cousens & Moss 1990).

Sowing time affects the expected weed free crop yield, Y_0, and the proportion of weed seedlings killed by cultivations during seedbed preparation. Hence, although later sown crops have a reduced expected yield, delaying sowing tends to improve weed control. Three sowing times are defined: early, mid and late. These map to crop specific dates – for example in winter wheat early = 1 September, mid = 14 October and late = 1 December.

It was not possible to fully parameterise θ (herbicide control) for all currently available commercial herbicides for all 12 crops. Therefore herbicide control in each crop is defined as low, moderate, moderately-high and high cost. For each crop, expert knowledge was used to estimate the percentage kill of each weed given the costing band of the herbicide programme. Cheap programmes were assumed to control weeds which are easy to kill, whereas more expensive programmes are needed to kill more resilient weeds.

The initial seedbank density

Practical estimation of seedbank density is difficult, so users are asked to stipulate the expected plant density of each weed species emerging in the crop during the autumn with the selected cultivations, in the absence of herbicides. This assessment is based on four plant density classes, which were normalised between species to give similar yield losses for each weed species. Hence, for a given class the density is lower for competitive weeds than for non-competitive ones.

Relating plant density to seedbank density present before autumn cultivations involves germination rates and the effect of cultivations. By assuming steady state conditions, we rearrange Eqn (5) to give

$$N_d = N_s(1-m)d/(1-(1-u)(1-m)) \qquad (6)$$

Substituting Eqn 6 into Eqn 1 and rearranging for N_s gives the estimate for shallow seedbank density. Deep seedbank density is then calculated using Eqn 6. In practice, the seedbank is unlikely to be in steady state, but this is an adequate approximation.

The stochastic dynamic programme

The SDP requires that the state variable (the weed seedbank density) is composed of discrete states. In our model this is made discrete by allocating the density of seeds in each seedbank layer to one of six non-overlapping ranges. For a single density state the model is run twice using the extreme values of the range. The resulting seedbank density values form the extreme values of a new interval that usually spreads over more than one of the defined ranges. Instead of selecting one state as the resulting state, the results are converted to a probability distribution. Consequently, the transition from one state to another is no longer deterministic. This is described in more detail below.

For each layer there are six classes, each with a seed density range from $L_l(i-1)$ to $L_l(i)$ where i is the index of the class (1 to 6), l is the layer (*s* for shallow or *d* for deep). $L_l(i)$ are species dependent values. The number of density classes (i.e. six) results from a compromise between model accuracy, which theoretically increases with the number of classes, and model run time, which increases with number of classes. For a single weed species, the state of the system is described by a pair of index values (i_s, i_d). If n weed species are simultaneously considered, the state of the system is therefore described by 2*n* index values. Each combination of these index values is a single model state, so the total number of states is 6^{2n}.

The six seedbank density classes need to relate to the four plant density classes used to define initial conditions (described above). It would have been simpler to relate six plant density classes to six seedbank density classes, but system evaluation concluded that users found it difficult to estimate more than four plant classes. The three plant density classes with the largest densities were split into four classes using a geometric progression (reflecting the way plant/seed numbers grow), and the fourth plant density class was split into two (Tatnell *et al.,* 2006). These six plant density classes map to the six seedbank density classes using Eqns 1 and 6, as described above.

The classifications were tested to ensure that the predicted number of plants in the first season was approximately the same as that set in the initial conditions.

The SDP formulation is

$$f_t(i) = \max_k \left\{ \sum_{j=1}^{N} p_{ij}^k (R_{ij}^k + \lambda f_{t+1}(j)) \right\} \qquad (7)$$

where $f_t(i)$ is the optimal expected financial reward for seasons t and beyond, given that the system state is i at the beginning of season t. Here, the system state describes the seeds in the seedbank and so i describes the $2n$ index pairs, so for example, in the one weed case (n = 1) $i = (i_s, i_d)$. The transition probability of going from state i to j given strategy k is denoted p_{ij}^k. The strategy describes a set of actions under which the system is run. R_{ij}^k is the financial reward associated with going from state i to state j given strategy k, and λ is a discount factor which scales future expected rewards. The discount factor is

$$\lambda = \frac{1+I}{1+\Omega} \tag{8}$$

where I is the current rate of inflation, here assumed to be 3%, and Ω is the interest rate, here assumed to be 6 %.

The solution of Eqn 7 comprises a set of decisions describing the actions that should be followed given the state at the beginning of season t: collectively a strategy for weed control throughout the rotation. The equation can be solved either to find a finite horizon solution or the infinite horizon solution (steady state solution). It is not always possible to find the latter, either because the system does not satisfy the necessary conditions for the existence of a solution, or because the problem does not converge within a reasonable time.

Calculating the transition probabilities

The SDP requires the probabilities associated with going from state i in season t to each of the possible states in season $t+1$ for a defined strategy. Ideally, each of the model parameter values should be described by a probability distribution reflecting the natural processes occurring. However, it is not always practical to assign a distribution to each parameter, either because of lack of appropriate data, or because the calculations are computationally too time consuming. Here, the uncertainty in seed number arises because the transition from one discrete state does not simply map to another single discrete state but onto a union of several intervals, as explained below.

When considering only a single weed species, the initial state is defined by $[i_s, i_d]$. To estimate the probability of ending up in shallow layer state $j_{s,}$ first the lowest and highest seedbank densities that can occur in season $t+1$ for a given strategy are calculated using Eqns 1 — 4. Because $N_s(t+1)$ is an increasing function of both $N_s(t)$ and $N_d(t)$, the lowest shallow seedbank density in season $t+1$ (ρ_L) is given when $N_s(t) = L_s(i_s - 1)$ and $N_d(t) = L_d(i_d - 1)$. Similarly, the highest shallow seedbank density in season $t+1$ (ρ_H) is given when $N_s(t) = L_s(i_s)$ and $N_d(t) = L_d(i_d)$. Further, it is assumed that having started in initial state $[i_s, i_d]$, the shallow seedbank density in season $t+1$ will lie in the range (ρ_L, ρ_H) with uniform probability. The probability that the shallow seedbank will be in state j_s in season $t+1$ is, therefore, given by the proportion of range (ρ_L, ρ_H) that overlaps the range defined by state j_s. That is

$$p_{[i_s, i_d], j_s} = \frac{\left\| (\rho_L, \rho_H) \cap \left(L(j_s - 1), L(j_s)\right) \right\|}{\left\| (\rho_L, \rho_H) \right\|} \qquad (9)$$

where $\| \ \|$ denotes the length of an interval. This concept is illustrated in Figure 1. A similar calculation is carried out to define the probability of going from state $[i_s, i_d]$ in season *t* to the deep layer state j_d in season $t+1$. In this case the possible range of values that can occur in season $t+1$ is calculated using Eqn 5.

The probability of going from state *i* to state *j* for more than one species is simply the product of the probabilities calculated for the single species.

Calculating the yield loss due to weed density

The total yield loss (Y_T) from all modelled weeds is assumed to be the sum of the losses from the individual species. Competition between species is low at densities found in most commercial situations in the UK (Bohan *et al*., 2005), so this is a reasonable approximation. The yield loss attributed to each species is deduced from the change in seedbank density from one season to the next. This is done by working backwards through the previous calculations. The seed rain is calculated from the change in seedbank density in the shallow layer by re-arranging Eqn 4

$$S(t) = N_s(t+1) - Q(t) \tag{10}$$

The number of seeds produced, $S(t)$, is determined by letting $N_s(t)$, $N_d(t)$ and $N_s(t+1)$ be equal to the midpoints of the ranges specified by states i_s, i_d and j_s, respectively. The number of mature plants (N_μ) is calculated by rearranging Eqn 2

$$N_\mu(t) = \frac{S(t)}{(1-h)v\beta - S(t)\alpha} \tag{11}$$

and substituting in the value $S(t)$ from Eqn 10. From the number of mature plants, the yield loss, Y_w, due to weed *w* is estimated;

$$Y_w = \frac{Y_0 r N_\mu(t)}{1+\gamma N_\mu(t)} \tag{12}$$

where Y_0 is the expected yield in a weed free crop and *r* and γ are species specific constants (Cousens, 1985). The financial benefit associated with going from state *i* in season *t* to state *j* in season $t+1$ for a given weed control strategy, *k*, is

$$R_{ij}^k = (Y_0 - Y_T)M - V - C - H \tag{13}$$

where *k* indicates the chosen strategy (which defines sowing time, cultivation, and herbicide control), Y_0 is the expected weed-free yield of the crop, Y_T is the total yield loss from the weeds, M is the crop market value, V are the variable costs associated with growing the crop, C is the cost of the chosen cultivation sequence and H is the herbicide programme cost.

Solving the dynamic programme

The time required to solve a SDP is proportional to the square of the number of states. In this problem there are 36 possible states for each weed (six density classes in the shallow and deep soil layers), so the time increases by a factor of 1296 for each weed added. To keep the run time to an acceptable duration, when the weed list contains more than two species, only the two most competitive species are considered. If there are two species of equal competitivity then the one with the higher initial density takes precedence. This approach produces a practically sound solution but not necessarily the optimum one.

The SDP was solved by backward recursion solution iteration (Howard, 1960), to determine the combination of weed control practices that give the best cost-benefit. In this method, a starting solution f_F is chosen that represents the final season's reward. Eqn 7 is then solved iteratively until either the solution reaches a steady state or a maximum number of iterations have been completed. The SDP with two weeds needed to be solved on a 2.8GHz personnel computer in less than a minute to be acceptable to users. The maximum number of iterations (seasons) achievable in this time was 10. Because the system is unlikely to have reached a steady state in this time, the estimate of f_F suggested by Sells (1995) was used:

$$f_F(j) = \frac{R_{jj}}{1-\lambda} \qquad (14)$$

where R_{jj} is the reward associated with going from state j to state j under an arbitrarily chosen strategy, and λ is the discount factor (Eqn 8) This terminal reward is a discounted result of staying in the same state and is a sensible choice (as opposed to zero, for example) as it will penalise high weed populations and so discourage strategies that are cheap in the early years but allow problems to build up.

Results and discussion

General overview

An example of Weed Manager's rotations module interface is shown in Figure 2 for three weed species. The top grid summarises the user defined cropping and cultural practices and the bottom grid summarises the resulting shallow seedbank densities and gross margin for each season. On the right hand side of the screen the expected gross margin over the rotation is indicated by an arrow on the bar. An estimate of variability is illustrated by the shading. Internally, the seedbank density is described by a probability distribution but it was not feasible to display all of this information comprehensibly on the graphical user interface (GUI) and so only the most likely seedbank density class is displayed.

Outputs from the model

The population dynamics of three weed species (*A. myosuroides, Anisantha sterilis* (L.) Nevski (barren-brome) and *Stellaria media* (L.) Vill. (chickweed)), in a 5 year continuous winter wheat rotation, were simulated. The model parameter values are given in Table 1. In these illustrative examples, initial seedbank density was a single value, not a range, and so results are deterministic. The simulation used contrasting combinations of cultivations, drilling dates and herbicide efficacies (Table 2) to explore the consequent changes in the seedbank. All simulations started with a seedbank of 2500 seeds m^{-2} distributed 80% in the shallow layer and 20% in the deep and a winter-wheat crop sown on 14 October (mid sowing) in Year 1 after non-inversion cultivation. Crop sowing date and primary cultivations were changed in subsequent years. The default herbicide treatment was assumed to achieve 90% control of emerged weeds in all years.

For *A. myosuroides*, rotation 1, the continuous non-inversion cultivation (minimal soil cultivation) on a mid date drilling, led to a steady increase in population size, despite a 90% kill annually from herbicides (Table 2). A plough in season three reduced the population in season five 19 fold in rotation 2 compared with rotation 1. Ploughing continuously from seasons two to five caused a 146 fold reduction in plant density in season five compared with continuous non-inversion (rotation 3 compared with rotation 1). Interestingly, in rotation 3, there was a small increase in plant density from season two to three, because ploughing for the second time brought viable seeds back to the surface. Non-inversion cultivations combined with drilling early in seasons two, three and four, caused a 1.2 fold increase in plant density in season four compared with a continuous mid drilling date in each season (comparing rotations 4 and 1). This effect of drilling date was because of the reduced kill of weeds in the early drilling. Correspondingly, drilling late in seasons two, three and four, caused a 2.2 fold decrease in plant density in season four compared with a continuous mid drilling date in each season (comparing rotations 5 and 1). Combining ploughing with early season drilling resulted in a substantial reduction in plant populations compared with continuous non-inversion cultivations (rotation 6 compared with 1), but the reduction was not as great as was achieved with ploughing in mid date drilling (rotation 6 compared with 3). Combining ploughing with late season drilling resulted in a further decline in plant populations (rotation 7 compared with 1 & 3). Ploughing was particularly effective in reducing populations of this weed.

The pattern of results for *A. sterilis* differed a little from *A. myosuroides*. The same trends were apparent, as ploughing and late sowing reduced weed survival (Table 2). The main difference was that population increase with non-inversion was faster and decline was greater with ploughing than they were for *A. myosuroides*. The latter is due to the absence of seed dormancy in this species (Table 1). Ploughing, consequently, achieved very good, but not complete control (rotation 3 compared with 1). Soil tillage and drilling late in the autumn resulted in greater kill of the population and thus more rapid decline in the seedbank.

The results with *S. media* were rather different. This species has more seed dormancy and so the proportion of seeds that germinate is lower than *A. sterilis.* It also is at more risk of invertebrate predation. As a consequence, the build up of populations in the non-inversion cultivated rotation (rotation 1) was slower and the rate of decline achieved by ploughing was much lower (Table 2). As with the two grass species, early cultivation and planting resulted in more plants emerging in the crop and so higher seedbanks than later cultivations. Again the ability of the second ploughing to return seeds to the soil surface and increase the seedbank was noticeable in seasons two and three of rotations 3, 6 and 7.

Model validation

The results of many simulations with all 12 species included in Weed Manager, were evaluated by three weed agronomists to assess whether the model conclusions were agronomically sensible. After several iterations the agronomists concluded that the results were realistic for UK conditions. More objective validation would have been welcome but the complexity (species, cropping, cultivation, weed control) and time scale available in the project made this unrealistic. This issue of the lack of independent validation of population dynamics models has been highlighted by Holst *et al.*, (2007).

Two data sets that were independent of those used to parameterise the models were identified. One described the response of *A. myosuroides* to non-inversion cultivation or ploughing over three years in a monoculture of winter wheat in France (Munier-Jolain *et al.*, 2002). Ploughing produced a rapid decline in population with in excess of 90% weed control in our model and in the observed data (Table 3). The non-inversion cultivations resulted in a decline in the observed plant density but not in our model, when 95% control was used. However, increasing the weed control in the model to 99.5% resulted in a decline similar to the observed data.

The second data set includes studies of *S. media* in a continuous wheat rotation in Germany, established either after ploughing or non-inversion cultivation (Knab & Hurle, 1986; Zwerger & Hurle, 2002). The observed weed population was low and after both cultivations there was little change, although there was a small decline with ploughing (Table 4). When using the weed control stated by Knab and Hurle (2002), our model predicted poorer weed control than that observed. For non-inversion cultivations with 63% control, our model predicted an appreciable increase in population. The predicted responses to non-inversion cultivations and ploughing were similar to those observed when the weed control was increased to 97 and 90%, respectively.

Neither data set was ideal for comparison with our model, but we failed to find any others. The model shows ploughing is more effective than non-inversion, which is borne out in the data. However, in both cases predictions for non-inversion cultivation showed much larger increases in weed numbers than in the observed data. The ploughing predictions were closer to the field data although weed numbers were still over-predicted. Without more experimental detail, for example on the depth distribution of the seeds in the soil, or the exact efficacies of weed control, it is hard to identify reasons for these discrepancies. As Weed Manager has been designed to suggest control strategies for weed populations it is better that it under estimates rather than over estimates expected control. This will make the system err on the side of caution.

The results of running the dynamic programme

The rotation selected by the user can be between two and five seasons (season 1 is the current season, which is fixed). When the SDP is run to optimise long term profits, the selected rotation is run for ten seasons. An example is given of continuous winter cropping with mainly winter wheat, infested with *A. sterilis* and *A. myosuroides* where the cultivation practice, the sowing period and the level of weed control has been defined by the user (Table 5a). High infestation levels for both weeds are predicted throughout the rotation. The optimisation of this scenario changes the cultural practices, replacing non-inversion tillage with ploughing, delaying sowing and increasing the expenditure on weed control (and therefore percentage control) (Table 5b). The increased weed control in all years, despite extra costs, resulted in higher crop yields and thus greater profits. The margin over the whole rotation increased by £94 and the variability is reduced. The preference for late drilling in the optimisation is understandable because the reduction in weed competition from late drilling often exceeds the drop in yield associated with the delay. However, in practice, farmers cannot sow all their fields 'late' but the practical message is to sow the badly infested fields last.

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Table 1. Model parameter values for *A. myosuroides, A. sterilis* and *S. media*

Parameter		*A. myosuroides*	*A. sterilis*	*S. media*
α	weed density parameter	0.0018[1]	0.002[3]	0.008[4]
β	number of seeds/plant	388[1]	120[3]	840[4]
g	proportion of seedbank germinating	0.30[2]	0.60[3]	0.27[5]
h	proportion of seeds lost to herbivory	0.55[1]	0.58[3]	0.78[5]
m	proportion of seeds that die/year	0.7[1]	1.0[3]	0.3[7]
v	proportion of seeds that are viable	0.55[1]	1.0[3]	0.95[6]

[1] Doyle et al., 1986; Moss, 1990; [2] Wilson et al., 1989; [3] Smith et al., 1999;

[4] van Acker et al., 1997; [5] Miller et al., 1998; [6] Sobey, 1981; [7] Conn and Deck, 1995

Table 2 The number of mature plants (m^{-2}) of the three test species surviving each season under the specified five year continuous wheat rotations.

Rotation number	Cultivations and sowing time in each season	*A. myosuroides*					*A. sterilis*					*S. media*				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	Tm, Tm, Tm, Tm, Tm	42.4	89.0	175	307	467	96.5	353	904	1406	1611	33.2	43.8	51.0	55.5	58.4
2	Tm, Tm, Pm, Tm, Tm	42.4	89.0	9.1	20.1	43.6	96.5	353	45.2	181	580	33.2	43.8	3.9	10.9	22.8
3	Tm, Pm, Pm, Pm, Pm	42.4	5.6	9.7	4.1	3.2	96.5	17.7	3.7	0.8	0.2	33.2	4.2	11.6	8.8	9.8
4	Tm, Te, Te, Te, Tm	42.4	106	240	459	591	96.5	436	1257	1930	1734	33.2	53.2	63.3	69.7	60.4
5	Tm, Tl, Tl, Tl, Tm	42.4	63.6	96.4	140	268	96.5	194	336	483	1073	33.2	37.1	42.3	45.7	56.3
6	Tm, Pe, Pe, Pe, Pm	42.4	6.7	11.8	5.4	3.8	96.5	21.8	5.6	1.5	0.3	33.2	5.1	14.1	11.2	10.5
7	Tm, Pl, Pl, Pl, Pm	42.4	4.0	6.8	2.5	2.4	96.5	9.7	1.1	0.1	0.0	33.2	3.6	9.8	7.1	9.3

Herbicides are set to kill 90 % of weeds each season.

Cultivations: P = plough, T= non-inversion cultivation

Sowing dates: early (e) = 1 September, mid (m) = 14 October, late (l) = 1 December

Table 3 Comparisons of the predictions of the Weed Manager model and the results of Munier-Jolain *et al.* (2002) for the response of *A. myosuroides* populations (plants m^{-2}) to different cultivations in a four- year continuous winter wheat rotation.

Origin of data	Sowing date	% weed control	Primary Cultivation	Cropping years			
				Yr 1	Yr 2	Yr 3	Yr4
Weed Manager	14 October	95	non-inversion	300	261	235	217
Weed Manager	14 October	99.5	non-inversion	300	83	25	8
Munier-Jolain	mid October	70-90	non-inversion	300	60	25	4
Weed Manager	14 October	95	Plough	300	21	29	10
Weed Manager	14 October	99.5	Plough	300	12	10	2
Munier-Jolain	mid October	90-97	Plough	300	30	<1	<1

Table 4 Comparisons of the predictions of the Weed Manager model and the results of Knab and Hurle (2002) for the response of *S. media* populations (plants m^{-2}) to different cultivations in a three - year continuous winter wheat rotation

Origin of data	Sowing date	% weed control	Primary Cultivation	Cropping years		
				Yr 1	Yr 2	Yr 3
Weed Manager	14 October	63	non-inversion	7	53	137
Weed Manager	14 October	97	non-inversion	7	7	8
Knab & Hurle	autumn	63	non-inversion	7	7	9
Weed Manager	14 October	45	Plough	10	6	26
Weed Manager	14 October	90	Plough	11	2	6
Knab & Hurle	autumn	45	Plough	11	3	6

Table 5 Example output from the Weed Manager model for infestations of *A. sterilis* and *A. myosuroides* in a rotation of all winter cropping: a) without optimisation b) with optimisation.

a)

Season	2005 / 2006	2006 / 2007	2007 / 2008	2008 / 2009	2009 / 2010	2010 / 2011
Crop	Winter wheat	Winter wheat	Winter oilseed rape	Winter wheat	Winter wheat	Winter beans
Cultivation	Plough	Non-inversion	Plough	Plough	Non-inversion	Plough
Sown	Mid	Mid	Mid	Mid	Mid	Mid
Cost (£/ha)	40 - 75	40 - 75	40 - 85	40 - 75	40 - 75	40 - 65
Number of seeds in the shallow soil layer at the end of the season						
black-grass	high	very high	high	very high	very high	very high
barren-brome	high	very high	moderate-high	moderate-high	very high	high
Margin (£/ha)	259	140	160	190	148	14

Average margin over rotation £152/ha (0-303)

b)

Season	2005 / 2006	2006 / 2007	2007 / 2008	2008 / 2009	2009 / 2010	2010 / 2011
Crop	Winter wheat	Winter wheat	Winter oilseed rape	Winter wheat	Winter wheat	Winter beans
Cultivation	Plough	Plough	Plough	Plough	Plough	Plough
Sown	Mid	Late	Late	Late	Late	Late
Cost (£/ha)	40 - 75	75 - 105	40 - 85	75 - 105	75 - 105	40 - 65
Number of seeds in the shallow soil layer at the end of the season						
black-grass	high	low-moderate	moderate-high	low-moderate	low-moderate	low-moderate
barren-brome	high	low-moderate	low	very low	very low	very low
Margin (£/ha)	259	307	194	320	322	72

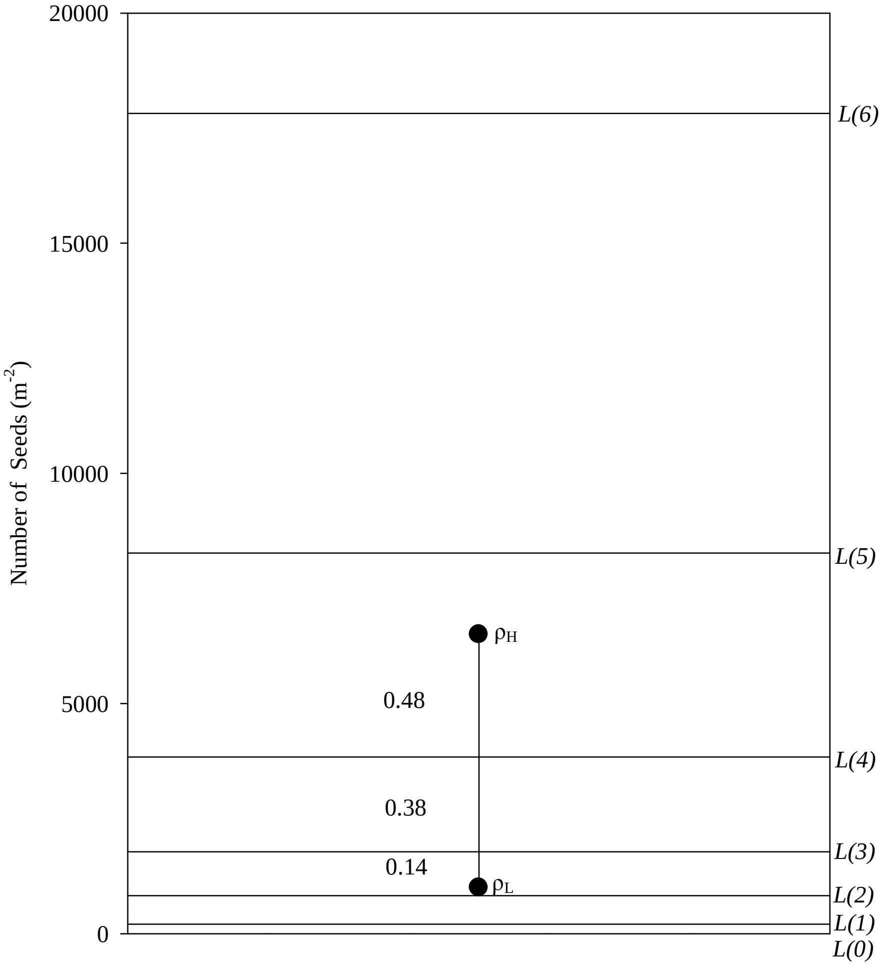
Average margin over rotation £246/ha (209-283)

Legend for Figures

Fig 1. An illustration of the span of seed densities in a soil layer in relation to the limits of seed density for different discrete soil density states. The horizontal lines represent the limits on discrete soil density states. The vertical line represents the maximum possible range of seed densities given the previous year's seedbank state and husbandry.

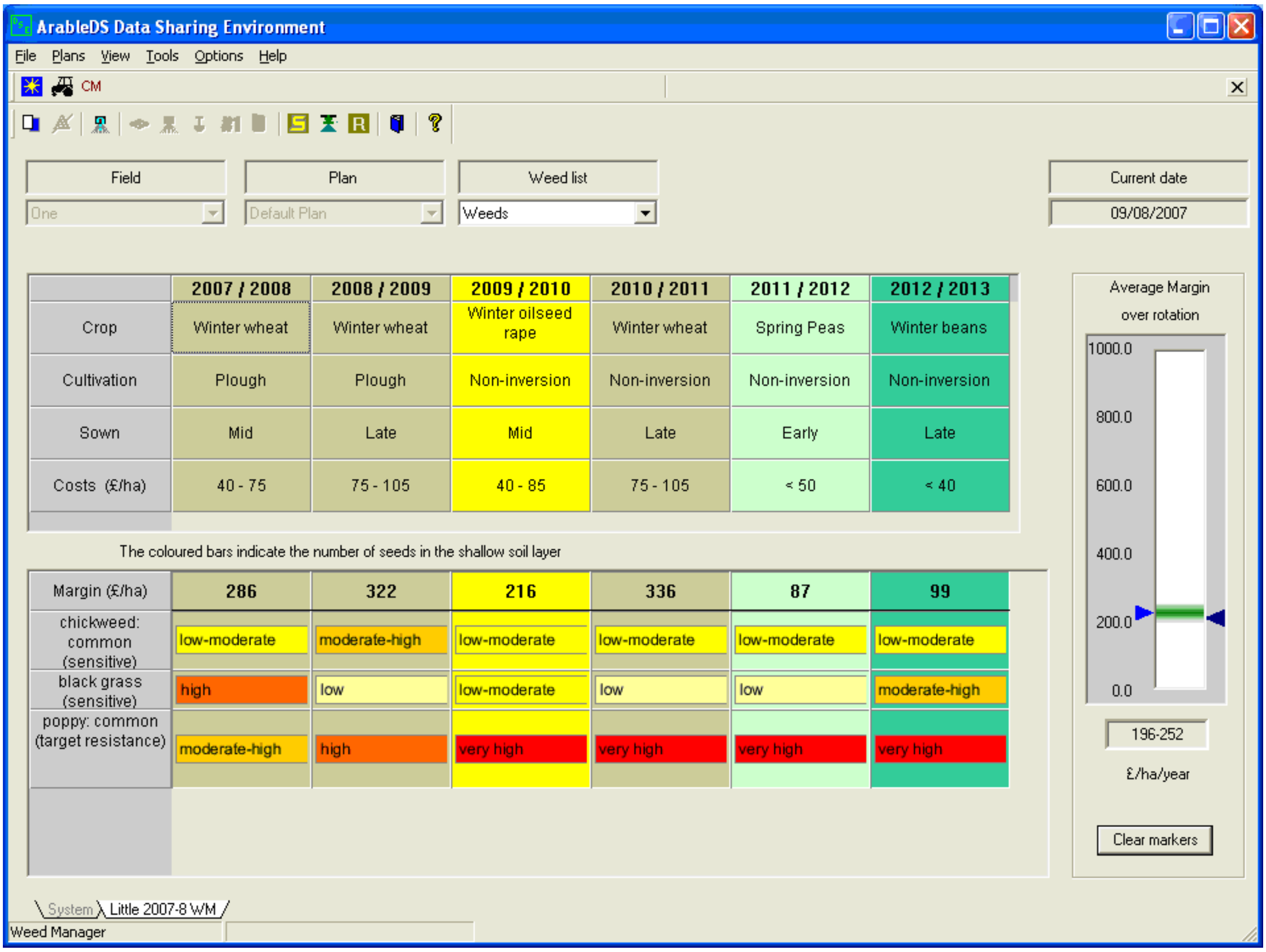
Fig. 2 An example of Weed Manager's rotational module interface, showing six seasons cropping, the gross margins each season (and the average rotational margin) and the responses of *S. media*, *Papaver rhoeas* L. and *A. myosuroides* seedbanks to different cultivations, sowing dates and herbicides.

Fig. 1



20000
15000
10000
5000
0
Number of Seeds (m-2)
L(6)
L(5)
L(4)
L(3)
L(2)
L(1)
L(0)
ρH
ρL
0.48
0.38
0.14

Fig. 2


ArableDS Data Sharing Environment
File Plans View Tools Options Help
CM
Field
One
Plan
Default Plan
Weed list
Weeds
Current date
09/08/2007
2007 / 2008
2008 / 2009
2009 / 2010
2010 / 2011
2011 / 2012
2012 / 2013
Crop
Winter wheat
Winter wheat
Winter oilseed rape
Winter wheat
Spring Peas
Winter beans
Cultivation
Plough
Plough
Non-inversion
Non-inversion
Non-inversion
Non-inversion
Sown
Mid
Late
Mid
Late
Early
Late
Costs (£/ha)
40 - 75
75 - 105
40 - 85
75 - 105
< 50
< 40
The coloured bars indicate the number of seeds in the shallow soil layer
Margin (£/ha)
286
322
216
336
87
99
chickweed: common (sensitive)
low-moderate
moderate-high
low-moderate
low-moderate
low-moderate
low-moderate
black grass (sensitive)
high
low
low-moderate
low
low
moderate-high
poppy: common (target resistance)
moderate-high
high
very high
very high
very high
very high
Average Margin over rotation
1000.0
800.0
600.0
400.0
200.0
0.0
196-252
£/ha/year
Clear markers
System
Little 2007-8 WM
Weed Manager