

Weed Manager – a model based decision support system for weed management in arable crops

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Abstract

Weed Manager is a model-based decision support system to assist arable farmers and advisers in weed control decisions on two time scales: within a single season and over several years in a rotation. The single season decision is supported by a wheat crop and annual weed growth simulation, with a multi-stage heuristic decision model. The rotational aspect uses a model of seed population dynamics, with decisions optimised using stochastic dynamic programming. Each time scale has its own user interface within a single program integrated into the ArableDS framework, which provides data sharing between several decision support modules. Weed Manager was used by about 100 farmers and consultants in the 2005–2006 and 2006–2007 seasons.

Keywords: weeds, decision support, models, optimisation, dynamic programming, stochastic, heuristics

1. Introduction

Weed control continues to cause major financial problems for arable farmers and, with the ever-increasing threat from herbicide resistance in both grass and broad-leaved weeds, the need to make the correct management decision is even greater. Targeting weed control and strategic planning over a whole crop rotation, through achieving maximum benefits from a combination of cultural and chemical control measures, may help to reduce costs. The need to balance crop production and farmland biodiversity, along with increased environmental awareness have become important issues, therefore an understanding of the longer-term implications of weed control strategies is required. In future, herbicide application will probably need to be targeted with more precision to meet EU water quality directives, while the number of available herbicides is reduced. Weeds form an important part of the farmland ecosystem, contributing food and hosts for insects, and providing food and cover for birds, an important indicator of biodiversity health. The use of weed management operations, especially herbicides, may have an impact on these functions (Marshall et al., 2003).

Several authors have used models of weed populations to investigate the economics of weed control (e.g. Cousens et al., 1986, Doyle et al., 1986). A typical approach has attempted to set thresholds for intervention (Coble & Mortensen, 1992, Berti et al., 2003, Nesser et al., 2004, Bennett et al., 2003). This may overlook the importance of rotation and other methods of cultural control in weed management. For example, the inclusion of spring crops in the rotation allows more autumn-emerging weeds to be controlled by ploughing and other cultivations, while crops other than cereals provide a wider choice of herbicides for grass-

weed control. An alternative approach, based on multi-season models of population dynamics, is the use of dynamic programming to optimise a weed control policy (Fisher & Lee, 1981; Sells, 1995). Most of these models have been research tools intended to provide information for use by extension services. More recently there has been growing interest in the use of computer-based decision support systems (DSS) to make these tools directly accessible by farmers and their advisers.

Probably the most successful in terms of the proportion of the industry using it, due to regulatory requirements, is the Danish PC Plant Protection system (Murali et al., 1999), which has sold over 2500 licences. It covers control of weeds, pests and diseases in wheat and other crops, including barley, peas and oilseed rape with an emphasis on reducing chemical use. Models are used to assess the need for control based on observations, then it gives recommendations of product choice and dose. Other approaches include the use of Bayesian networks in a DSS designed for growing malting barley without pesticides (Kristensen & Rasmussen, 2002).

In the UK, the Arable Decision Support (ArableDS) initiative was intended to provide a range of computer-based decision support tools for farmers and advisers. It is the result of a series of research and development projects starting in the mid 1990s, and now aims to include a wider community of users and developers (Parsons, et al., 2004). Weed Manager is a DSS module designed as part of the ArableDS suite running on Microsoft Windows™. Weed Manager provides farmers, agronomists and distributors with a robust tool to plan and develop weed management strategies. In order to ensure that Weed Manager met the needs of the industry, it was developed with the involvement of users (farmers, agronomists and distributors) at all stages of the project, from the initial design to testing the decision making processes.

The system consists of a within season planning tool to investigate a range of weed management strategies in a winter wheat crop in a single season, and a rotational planning tool allowing users to consider weed control options over several years. A survey of French farmers also found that they considered different time-scales for decision making: current year, rotation and long term (Macé et al., 2007).

Both parts of the system are model based, using data specific to individual farms. There are a comprehensive herbicide database and an encyclopaedia within the system, containing information on approximately 150 herbicides used in winter wheat. The weeds encyclopaedia contains detailed information on the biology, life cycle, geographic location, identification and control measures for over 140 key arable weed species, along with photographs of all the key growth stages from cotyledon through to flowering. Additional information on environmental impacts, herbicide resistance, biodiversity and cultural control measures are all included (Tatnell et al., 2006). The environmental information includes the statutory environmental protection information and copies of Environmental Impact Sheets listing the risk to six classes of organisms plus soil water and groundwater, produced under the Voluntary Initiative, a programme agreed between the agrochemical industry and the UK government. Weed Manager contains a full help system to guide the user when required.

This paper gives an overview of the design of Weed Manager, the user interface and the underlying models. The models are described in more detail by Benjamin et al. (in press) and Tatnell et al. (2006). Additional information is available from www.weedmanager.co.uk.

2. System architecture

Weed Manager, in common with several other ArableDS tools, operates as a module within the ArableDS Data Sharing Environment (DSE) and uses the same basic agronomic, pesticide, weather and user data. These programs have common user interface elements to help users to learn how to use the system (Parsons et al., 2004).

The outline structure of the system is shown in Fig. 1. All the data are stored in Microsoft Access™ databases that are accessed via dynamic link libraries (DLLs). The encyclopaedia is displayed in the Rothamsted browser (Tatnell et al., 2006), which uses the Microsoft Web Browser component to display the encyclopaedia pages. The decision support module has been developed in Microsoft Visual C++™ V6.0 using object oriented, component based software development methods to ensure that the system can be extended to encompass more functionality as required and could be developed on multiple sites. Each component is described in more detail below.

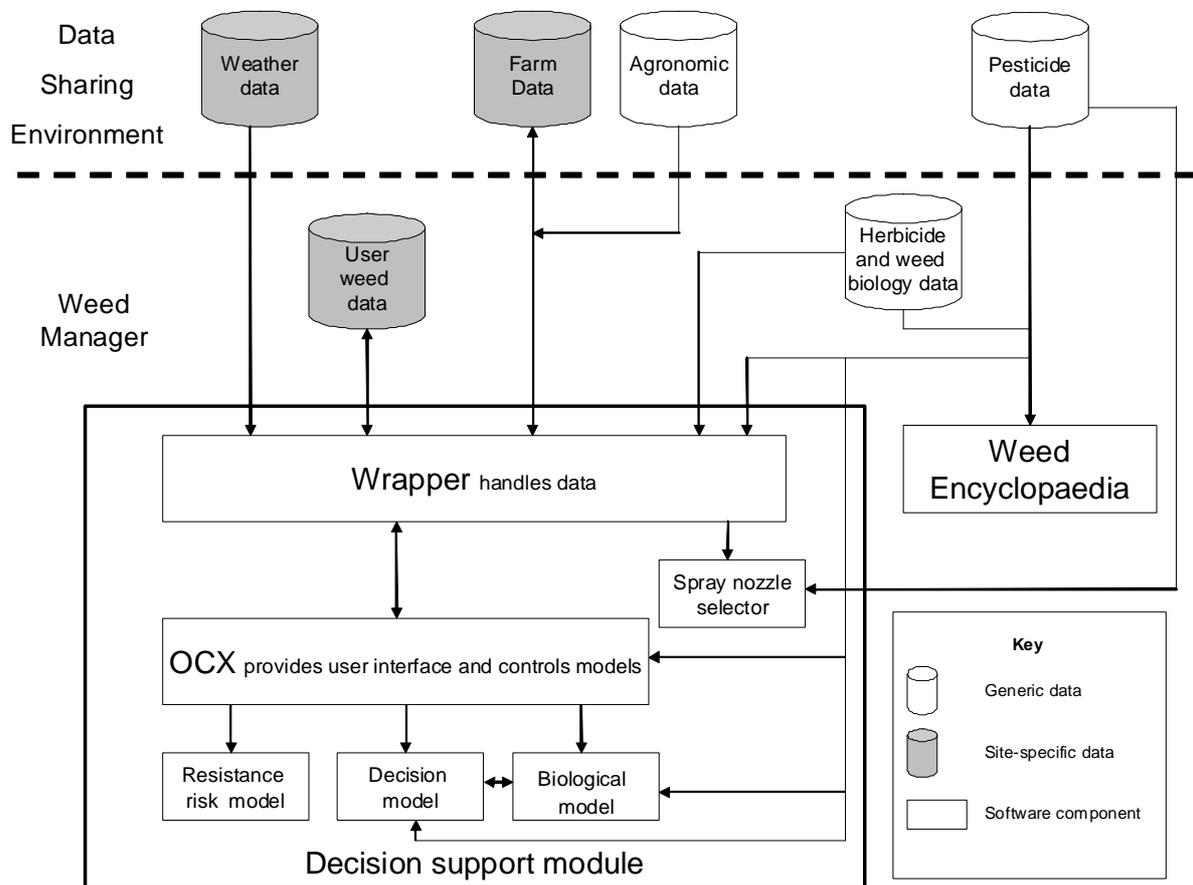


Fig.1. System architecture of Weed Manager and links to the Data Sharing Environment

2.1 The wrapper

The wrapper component is an Object Linking and Embedding (OLE™) in-place and automation server, which was generated using the Microsoft Application Wizard and so uses the document/view architecture of the Microsoft Foundation Classes (MFC™). The document class provides all the data handling and manages retrieval of the user's data from the DSE. The farm and weather data are supplied in intermediate databases that are accessed

using DLLs as described below. Weed Manager can read and update the farm database, but can only read from the weather database. Changes to the cropping information, farm costs and observations are stored immediately. The treatment programmes, consisting of cultivations and sprays are stored only when requested by the user to allow them to test different scenarios without affecting the underlying data. When the user switches to a different module in the DSE or closes Weed Manager, it offers the option to save modified plans.

2.2. The OCX

Most of the handling of the user interface and the models in Weed Manager is implemented in an ActiveX™ control (OCX), which is a separately compiled module. The use of an OCX to implement the user interface and model interactions gives several benefits. Firstly, it separates database handling from user interaction. Secondly, it allows the inclusion of the system within a different wrapper program. Finally, it solves some technical difficulties that occur when using multiple views in an in-place server. Taken together these considerably simplified development.

The user interface contains two views (see Fig. 2 & 3), one for assistance with within season control of weeds in winter wheat and one for control of weeds in a rotation of up to 6 years. The user interface is discussed in more detail in Section 3.

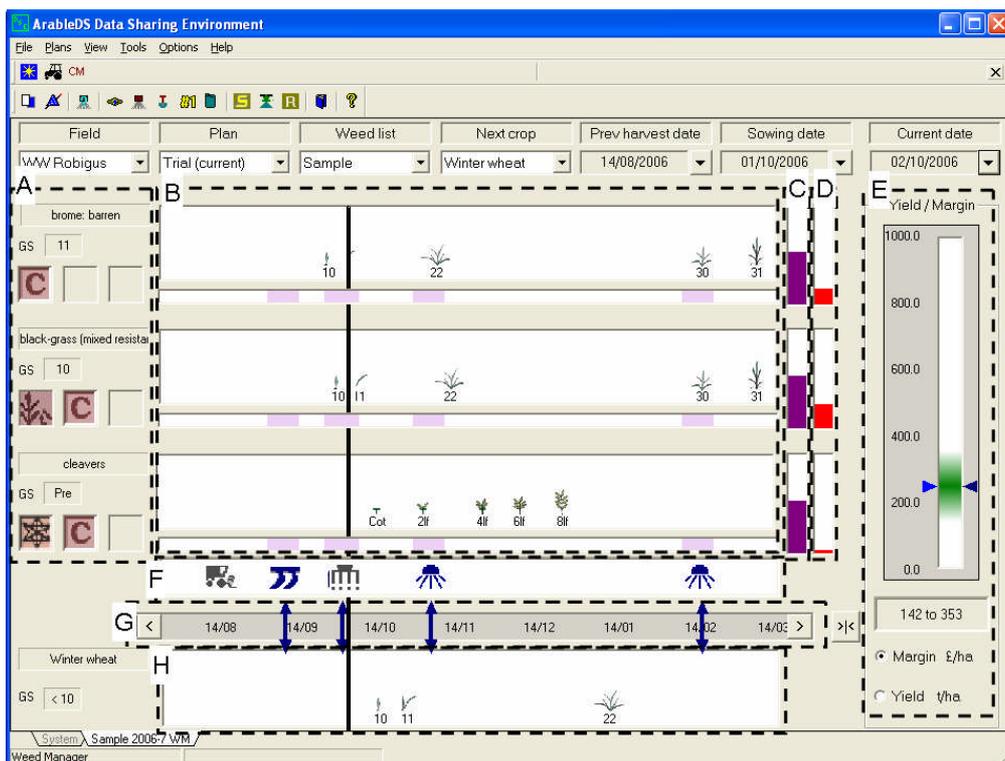


Fig. 2. Weed Manager user interface: within season view. (A) Weeds and information icons. (B) Weed growth stages. (C) Weed kill by cultivations and herbicides. (D) Yield loss due to each weed. (E) Partial gross margin, showing variability by shading. (F) Icon bar showing harvest, plough, harrow/drill and two sprays. (G) Date bar. (H) Crop growth stages.

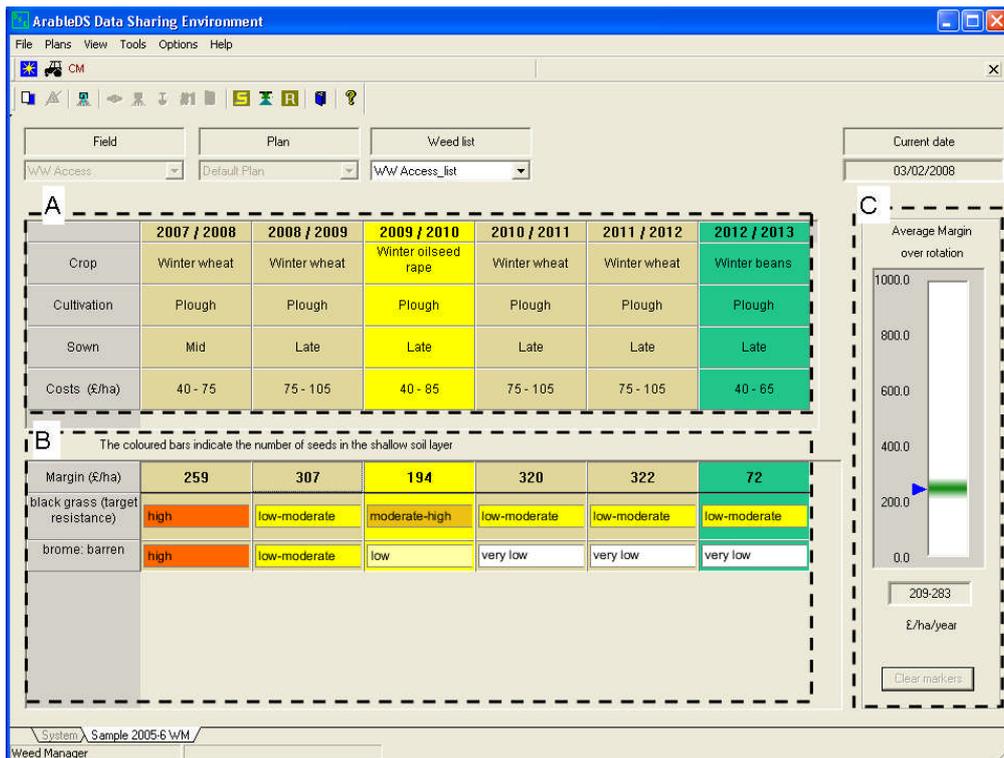


Fig. 3. Weed Manager user interface: rotation view. (A) Input grid: crop, cultivation, sowing date and spray cost by season. (B) Output grid: margin and weed seedbank by season. (C) Average gross margin over rotation, with shading showing variability.

2.3. The data

In Fig. 1, the data shown above the dotted line are provided by the DSE. The data below the line are part of Weed Manager.

The pesticide data provided by the DSE consist of the statutory information relating to the herbicides that can be used in winter wheat, including restrictions on maximum doses and timing of applications, with additional information on permitted and prohibited tank mixes. This information is imported from the LIAISON database (www.liaison.csl.gov.uk) developed by the Central Science Laboratory based on data supplied by the UK Pesticide Safety Directorate (Thomas et al., 2000). The information regarding the dose and timing of applications is converted from text into mathematical terms for use by the decision support process models. In addition, the pesticide database contains default values for the cost of each pesticide and some statutory label data relating to the application of the product. The data can be viewed by users through the encyclopaedia.

The agronomic database provides default values for drilling and harvest dates, crop value, basic costs for operations such as ploughing and spraying as well as values for the variable costs associated with each crop. This ensures that the same defaults are available for each DSS within the ArableDS framework.

In order to predict the plant growth over the complete season, the system uses weather data from the DSE. It combines the weather data for the current season (referred to as user weather) with climate data for the most appropriate of 26 regions in the UK to provide weather data for the full season. The user weather data are specific to each site and can be

entered manually, transferred from a data logger or downloaded from the ArableDS web site, with over 100 possible weather sites being available. Users can also add their forecast data.

The climate data sets are intended to provide representative data for the models when forecasting future outcomes and were designed in consultation with the developers of several decision support modules. Each set contains 12-year means of the daily temperature, solar radiation, wind and transpiration data. Because rainfall is a sporadic event, and the magnitude of the event is important for some applications, such as forecasting splash-borne diseases and runoff, daily means are not appropriate. The method used is designed to ensure that statistics including the 5-day total (or mean) and the numbers of dry and high rainfall days are maintained. The year is divided into 5-day intervals and the 12-year means of the total rainfall and the numbers of dry days and days with more than 5 mm rain in each period are calculated. The climate data set is then constructed to ensure that these properties are preserved. In the case of Weed Manager, the important statistic is the 5-day total rainfall, which is used to calculate the soil moisture, on which seed germination depends.

The farm-specific data consist of farm location, field and cropping information, including observations of plant growth and treatment plans. The database also stores the herbicide application, cultivation, herbicide and variable crop costs entered by the user, which override the default values in the agronomic database. The farm data provided to the decision models therefore uses a combination of the user's own information and that supplied by the DSE.

In addition to the shared data provided by the DSE, Weed Manager requires its own weed and herbicide information to: populate the encyclopaedia, provide parameters for the models predicting crop and weed growth, and to estimate the costs of controlling each modelled weed in each crop. The key parameters are discussed within the descriptions of the models.

3. User interface

The within season and rotational management decisions are represented by two separate views, each filling the main window (Fig. 2 & 3). The user can rapidly switch between them by clicking on a button on the toolbar. The rotational screen reflects the cultivation choices the user has made in the within season view, so always shows winter wheat and the current weeds and cultivation decisions. Each view is linked to a biological model and a decision model, which are described in Section 4.

3.1. The within season view

The first time Weed Manager is used on a new farm a weed list has to be created. The weed list editor opens automatically (Fig. 4) and the user can choose the weeds of interest and estimates of their expected density in the crop in terms of four density classes, and save these as a weed list. The user can create new lists or edit existing ones at any time.

Subsequently, Weed Manager opens in the within season view (Fig. 2), which can be used at any time from just after harvest of the previous season's crop to just before harvest of the current season's crop. The screen layout shares many features with other ArableDS programs. Below the usual menu and toolbars, there is an information bar showing basic details of the field crop and key dates. Each date, including the 'current date' on which planning is based, can be changed by clicking the control to its right.

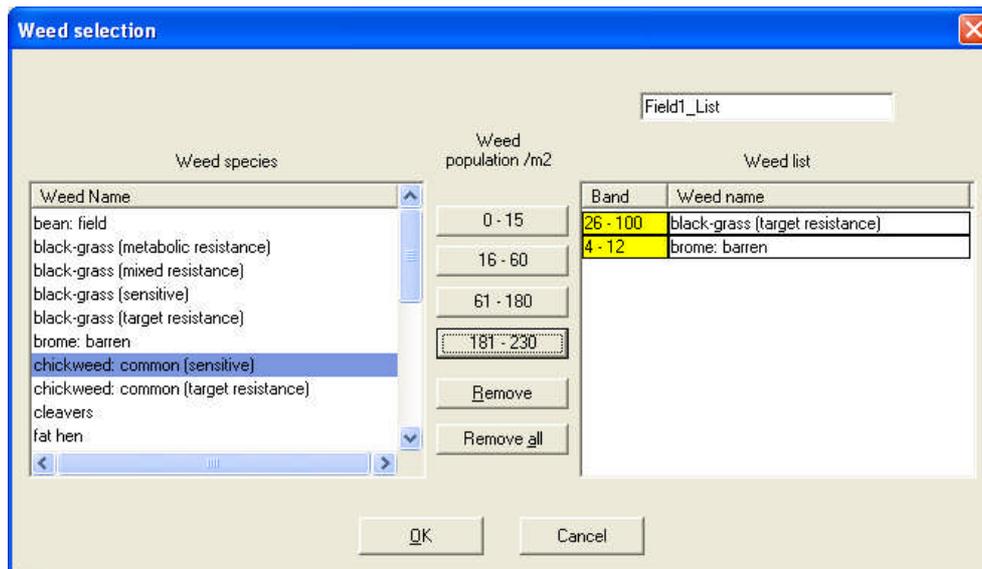


Fig. 4. The Weed Manager weed list editor. The panel on the left shows the weeds available in the model; the buttons in the centre show the population density classes, which are weed-specific; and the panel on the right contains the currently selected weeds at the densities estimated by the user.

The main area of the screen shows a pictorial representation of the development of the weeds and the crop as calculated by the biological model. There is a horizontal panel for each weed showing the progression of growth stages calculated by the model. This is linked to the date bar (or time line) that runs across the screen, just above the panel showing the crop growth stages. Above the timeline is another bar with a set of icons representing cultivation and spraying operations performed on the crop. Each icon is linked to a double-headed arrow on the date bar, which may be dragged sideways to adjust the operation date. The whole display can be scrolled sideways using the arrow buttons at the ends of the date bar, or zoomed in and out to show a different range of dates.

Additional information on each weed is provided down the left of the screen. Up to three icons can be displayed to indicate features such as sensitivity to frost, or importance for wildlife. To the right of the growth stage panel for each weed, two vertical bars display the kill rate calculated by the model for the current cultivation and herbicide sequence (adjacent to the growth stage pane) and the yield loss resulting from the weed population (to the right of the kill rate bar). On the extreme right of the screen another vertical bar shows the predicted yield or margin over herbicide and cultivation costs for the proposed treatment strategy and the degree of uncertainty in the estimate. This uncertainty is calculated by running the model using the minima and maxima of the weed density classes selected by the user. Variable costs other than herbicides and cultivations are not included in the margin calculation, because they are not affected by the decisions being considered.

In addition to dragging the arrows to change the times of operations, the user can edit the cultivation plan and the spray plan by clicking on toolbar buttons or selecting the corresponding commands from the menu. These present similar dialogs showing the current plan and the available cultivations or herbicides (Fig. 5). Operations can be added on any date or removed from the plan. Herbicides are chosen by product name and the required dose can also be chosen from the ones available for the product. To reduce the need to select from a

long list of all the available herbicides, the chemical list editor is used to create a short list of products appropriate to the user that will be displayed when choosing treatments and used in the decision model.

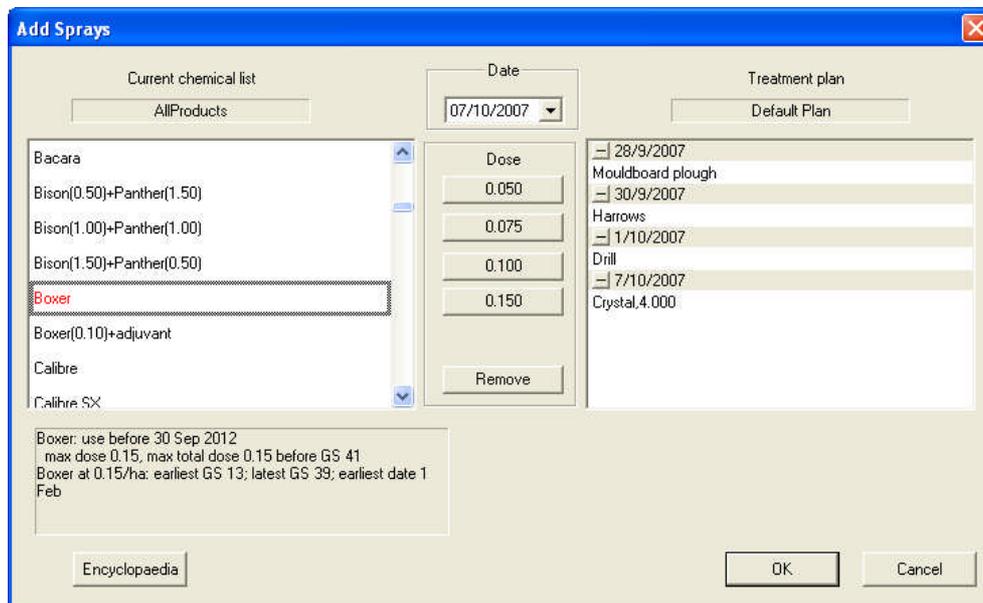


Fig 5. The Weed Manager spray plan editor. The panel on the left shows the available herbicides, with application restrictions for the selected product below, the middle panel contains buttons for the available doses; and the panel on the right shows the current spray and cultivation plan.

The settings dialog can be used to change the crop-dependent information, such as the expected yield, density, variable costs and grain price. As the season progresses, it is also possible to add observations of the crop and weeds, giving the growth stage and the density observed on a particular date. These are used to revise the predictions of the model, increasing the accuracy.

These features make it very easy to experiment with different cultivation sequences and herbicides to see their effect on the weeds, the crop yield and the margin. However, the range of options is huge, and it may be difficult to find the best combination. To help with this, the system includes a suggest treatments feature. To ensure a reasonable response time, the user must first select a chemical list of 50 products or fewer. The program will then search through thousands of combinations of cultivations and herbicide programmes to produce a list of those that give good margins. This is described further in Section 4.3. Having obtained a list of programmes, one can then be selected for more detailed examination in the main view.

3.2. The rotational view

The rotational view (Fig. 3) allows the consequences of weed control decisions to be examined over 6 years. The information area below the tool bar and the display of yield and margin on the right hand side, are similar to the within season view. However the rest of the screen is rather different from that view and most of the other ArableDS programs, which focus on single-season decisions.

Most of the screen is occupied by a grid in which the columns represent growing seasons. The upper part of the screen has rows showing the crop, type of cultivation (plough or non-inversion), sowing date (early, mid or late), and herbicide costs (divided into four classes). The crop and cultivation for the first year are fixed by the within season decisions; any of the other pieces of information can be changed directly by clicking on the grid cell and selecting from a pop-up list. The results of changes are recalculated immediately and redisplayed.

The lower part of the screen shows the results of the model. The biological model, which is described in section 4.2, simulates the population of weed seeds for each species in the shallow and deep soil layers, although only the shallow layer is displayed. The changing populations are shown both as words and colour codes, ranging from white (very low), through shades of yellow to red (very high). These give instant feedback of the state of the seedbank. The top row of this section of the screen shows the average gross margin calculated by the model for each year. It provides a vivid and highly interactive illustration of the way that decisions taken in one season can have consequences for many years to come.

As with the within season view, this screen can be used interactively, or optimised by choosing the suggest treatments command once the rotation has been fixed. In this case the user can choose how many years, up to 5, to include in the rotation. The decision model (section 4.4) finds the optimum strategy for the whole rotation consisting of cultivation type, sowing date (early, mid or late) and herbicide cost, and presents it on the screen.

4. Models

4.1. The models of weed and crop development within a season

To provide the information for the within season view, Weed Manager contains models of the growth of wheat and weed species, and the effect of the weeds on the wheat yield. A previously established growth stage model of Milne et al. (2003), which was used in the ArableDS Wheat Disease Manager project (Parsons et al., 2004), was extended to include more detail of the early growth stages. In the model, leaf, tiller, node and ear development in wheat are associated with the temperature and day-length. Using the same model, parameter sets relating development to the input variables were developed for the grass-weed species being considered. A similar approach was taken for broad-leaved weeds except that the number of stages calculated was smaller. The species-dependent parameters (about 40 in total) are held in the weed biology and herbicides database.

The model does not attempt to predict yield, because it depends on factors other than weed management; instead the user is asked to enter the expected yield in the absence of weeds. The model predicts yield-induced weed loss based on the assumption that the yield loss due to a population of weeds depends on the relative green area indices of crop and weeds at a given point in the canopy development, according to the model of Kropff et al. (1995) with a separate competition parameter for each species. The point used is when the total green area index (GAI) of crops and weeds is 0.75, and this is referred to as canopy closure. The models simulate the development of the crop and multiple weed species, in particular the growth of their leaf areas, from germination to canopy closure. The growth of each species in the community is simulated using an ecophysiological model (Kropff & van Laar, 1993). The crop is simulated as a single cohort of plants germinating simultaneously, whereas each weed species is simulated as eight cohorts to account for the distribution of germination dates that will occur. The first to emerge is displayed on the user interface. The timing of the emergence

of these cohorts is based on a polynomial model for each weed fitted to the pattern of seasonal emergence summarised by Evans (1962).

The sowing density for the crop is specified by the user, allowing the total canopy size to be calculated. Again, this affects only the yield loss estimate: the expected yield is set by the user. The weed seed population is unknown, so instead the user specifies the plant density emerged or expected to emerge. As precise estimation of density is difficult, it is entered as one of four classes (low, medium, medium/high, high) described by a density range, as shown in Fig. 4. The model can be corrected during the season by further observations of density, ground cover or growth stage of the crop or weeds. The model simulates germination, emergence, development and growth, driven by daily weather data (temperature and rainfall).

The effect of herbicides is simulated by reducing the weed GAI according to the sensitivity of each weed to the herbicide, based on data provided by the manufacturers. Each weed is classed as eliminated by (G), susceptible (S), moderately susceptible (MS), moderately resistant (MR) or resistant (R) to each herbicide at each of its growth stages.

Cultivation operations act in several ways. Those that are used after drilling, such as tine weeding, are treated in the same way as herbicides. Non-inversion operations before drilling, such as harrowing, kill the emerged seedlings, but have no effect on the ungerminated seeds. Ploughing inverts the soil to a depth of about 250 mm, and in doing so kills the emerged seedlings, but brings to the surface a new population of seeds. It thus stimulates further germination and emergence.

The model has been fully parameterised for 12 weed species: *Alopecurus myosuroides* Huds. (black-grass), *Anisantha sterilis* (L.) Nevski (barren brome), *Avena fatua* L. (wild oats), *Lolium multiflorum* Lam. (Italian ryegrass), *Poa annua* L. (annual meadow-grass), *Stellaria media* (L.) Vill. (common chickweed), *Galium aparine* L. (cleavers), *Papaver rhoeas* L. (common poppy), *Chenopodium album* L. (fat hen), *Polygonum aviculare* L. (knotgrass), volunteer *Vicia faba* L. (field beans) and volunteer *Brassica napus* L. ssp. *oleifera* (oilseed rape). Where relevant, parameters are also included for herbicide resistant biotypes. The model is described in more detail by Tatnell et al. (2006).

4.2. The model of weed dynamics in a crop rotation

The biological model of weed dynamics was designed to provide the quantitative information for the rotational view in the Weed Manager program and to be used by the corresponding decision model. A detailed description can be found in Benjamin et al. (in press) and Tatnell et al. (2006).

The model is based on the life cycle model developed by Moss (1990) for *A. myosuroides*, but can be applied to many annual plant species. In essence, it is based on estimation of seed fecundity and survival. Similar models have been proposed by Doyle et al. (1986) and Cousens et al. (1986) to describe the life cycle of *A. myosuroides* and *A. fatua* (wild oats), respectively. Because of the large uncertainties present in the weed life cycle, it is necessary to describe the population changes by probability distributions, potentially leading to a stochastic model. However, if probabilities were used for every step the model would be unnecessarily complicated. In the present model, the population is described by a distribution, but the operations performed on it are deterministic.

The state variables in the model are the seedbanks (seeds/m²) immediately after harvest in two layers: the shallow layer, 0–50 mm, and the deep layer, 50–250 mm. Unless disturbed by cultivations, seeds in the shallow layer could potentially germinate during the autumn, whereas those in the deep layer must be brought up to the shallow layer in order to germinate.

A series of processes determines the seedbank in the following year. Cultivations cause an exchange of seeds between the two soil layers. Ploughing moves almost all of the seeds from the shallow layer to the deep one and brings up a substantial proportion of seeds from the deep layer. Non-inversion cultivations cause a much lower proportion of the seeds to be exchanged between the shallower and deeper levels. A proportion of the seeds in the shallow layer germinate to produce seedlings, depending on the time of year and the periodicity of emergence of the species. Some of these are killed by cultivations or herbicides, the remainder develop into mature plants. The yield loss is estimated from the mature weed density using the same method as the within season model. The mature plants produce seeds, of which some are non-viable and some are lost to herbivory. The remaining viable seeds are added to the shallow layer. At the same time, a proportion of the ungerminated seeds in the soil seedbank die during the year. The model is intended to simulate expected behaviour, with seasonal variability included as part of the uncertainty, so the processes described above do not depend on weather data.

The model has 11 species-dependent parameters describing seed or plant survival in each step, emergence timing (common to rotational and within season models) and seed production. These are stored in the weed biology and herbicides database. The parameters describing the effect of cultivations on the transfer of seeds between the soil layers are independent of the species.

The herbicide component of weed management strategies is not described by a detailed list of herbicides, but by the herbicide cost level, with four cost bands depending on the crop. The kill rate of each combination of crop x weed x cost is stored in the weed biology and herbicides database, filled according to peer-reviewed expert knowledge.

To enable the weed control programme to be optimised by the decision model, the seedbank variables are divided into discrete ranges. These are related to the classes used to set the initial weed density for the within season model, but the full range is divided into six classes instead of four to give greater resolution, using a method described by Benjamin et al. (in press). When the full series of transitions is applied to a single seedbank class to estimate the seedbank in the following year, the resulting values form an interval that usually spreads over more than one class. Instead of selecting one class as the resulting state, this result is treated as an element of the uncertainty observed in practice, and converted to a distribution by assuming that the probability of arriving in a class is the proportion of the interval that intersects the class.

4.3. The decision model for management of weeds within a season

The within season decision model is used when the user selects the suggest treatments command from the within season view in Weed Manager. The objective is to suggest a range of different herbicide and cultivation plans that result in good margins for the current season. The margin used is the value of the grain less the herbicide and cultivation costs, all of which may be changed by the user. Because the problem consists of numerous discrete decision variables (for example each herbicide x dose x timing x weed combination has a discrete

efficacy), it was not possible to develop an efficient optimisation algorithm. To achieve the desired response time of less than 1min on a typical office PC, a heuristic was used to provide good, but possibly not optimal, solutions. The decision model is described in more detail in Tatnell et al. (2006).

The biological model has three main aspects that are relevant to the decision model: the timing of emergence of the crop and cohorts of weeds; the growth of the crop and untreated weeds to canopy closure; and the impact of treatments on the GAIs at the time of canopy closure. This separation of the effects of pre-drilling cultivations, which affect emergence, and herbicides, including post-drilling cultivations, is important for the decision model, because the effects of herbicides on yield can be evaluated very quickly, whereas any operation that changes the timing of canopy closure requires a full run of the model. The decision model generates and compares feasible treatment programmes, operating in a series of phases to reduce the time taken to reach a set of solutions.

The first phase only takes place if the decision is being made before drilling. It generates three types of sequences of feasible cultivations: sequences including ploughing, using non-inversion cultivation only and direct drilling only. These are evaluated to find the one in each type that gives the highest margin. Some types of sequence may be excluded if the timing of the decision restricts the number operations that can be carried out before drilling.

Having chosen up to three cultivation sequences, the second phase filters the working list of herbicides chosen by the user, to select those appropriate to the weeds present. Some herbicides can be applied at different doses, but there are several rules that restrict when they can be applied, when they will be most effective and which mixtures can be used. The decision model defines four consecutive spraying periods: pre-emergence, autumn, spring and desiccant. Within each of these, application dates are selected at intervals of 14 days. Each herbicide is checked against the rules at each of these application dates; those that pass are then considered in the next phase. The post-drilling cultivations are added to the list for appropriate periods.

In the third phase, the effect of each herbicide is evaluated at each of the timings within each spray period to find which timing in each period gives the lowest yield loss. All permitted mixtures of two products are evaluated in the same way. Any product or mixture that is not superior to a cheaper one is eliminated. The result is a list for each period containing applicable herbicides and mixtures with their best timings.

The fourth phase uses the results of the third to evaluate all the permitted programmes containing combinations of the remaining herbicides and timings. This results in a list of programmes, ranked by the resulting margin or, if preferred, yield.

In the final phase, the list of programmes is filtered to remove poor solutions and repetitions of very similar programmes, because the users preferred to see fewer, more diverse suggestions. All solutions giving a margin less than 90% of the best are removed and, if necessary, similar solutions are progressively removed until fewer than 20 remain.

4.4. The decision model for management of weeds in a rotation

The rotational decision model is used when the user chooses the suggest treatments command from the rotation view. Using the biological model of seedbank dynamics, it optimises the

choice of sowing date, type of cultivation and herbicide cost to find the best strategy throughout a rotation of up to 6 years defined by the user. Full details are given in Benjamin et al. (in press) and Tatnell et al. (2006).

The optimisation is a finite horizon, stochastic dynamic programme, solved by backward recursion solution iteration (Howard, 1960). The solution is the policy that maximises the long term expected discounted return. A policy defines the decision to take for every possible state of the system. The dynamic programme maximises the expected discounted return over a period of 2–4 rotations (8–10 years) depending on the length of the rotation.

As described above, the biological model is a simulation of seedbank dynamics using two soil layers with six seedbank density classes in each. The state variable for a single weed is then a pair of integers (i, j), each having six possible values, the class numbers, representing the number of seeds in each layer following the harvest of the previous crop. The decision variables are the sowing date (early, mid or late), the type of cultivation (plough or non-inversion) and the herbicide cost (in one of four cost bands). The choice of crop is not a decision variable: the user must choose the rotation before attempting to optimise the other decisions. The model takes the state and the decision, and predicts the probability distribution of states at the end of the year, that is, the seedbank following the next harvest, and of the yield loss, and hence cost, for the season.

The return from a single year is the gross margin for the crop. This is calculated from the base yield, the yield loss due to weeds, the crop price, a cost for the type of cultivation, the herbicide cost and a crop-dependent sum for the other variable costs. The expected return for a single year is the sum of the returns for all the possible states, weighted by their probabilities. The expected return over the period of the optimisation is the mean of the returns for the years, weighted by a discount factor to account for interest and inflation, and a terminal return for the state in the final year. The terminal return is required in a finite horizon dynamic programme, because the final state will have an effect on future years. Without it the cost of leaving a high final seedbank would be underestimated. The value used is the single-year return that would result if the system was maintained in steady-state, weighted by the discount factor (Sells, 1995).

After optimisation the display shows the result obtained by taking the most probable seed population and the corresponding decision each year.

The solution time places a limit on the number of weeds that can be optimised simultaneously. Each weed has 36 possible states (6 for each layer), so the solution time increases by a factor of 36^2 (1296) for each weed added. This was illustrated by a test on a 2.4 GHz Pentium 4 PC, in which the solution for two weeds required about 15 s, and for three weeds required 15540 s (over 4 hours). As a result, Weed Manager simply considers the two most competitive weeds in the optimisation.

5. User consultation and testing

5.1. User consultation

A series of user activities took place between December 2000 and October 2004. In the early development phase of the project the users were consulted and provided feedback on the

screen design and content of the system, through a number of workshops at various locations in England and Scotland. A number of key points were highlighted from these early consultations that focused the development. These included:

1. Easy data entry and links to other systems.
2. Understanding and confidence in system assumptions.
3. Optimise and compare future strategies.
4. Manage herbicide resistance in tactical and strategic decisions.

A group of users was established and consulted during the project. Despite problems at the early stages with recruiting and maintaining numbers (Parker et al., 2004) useful feedback was received at several stages in the project. Additional user involvement included a postal survey, email consultations and detailed telephone interviews.

Between March and October 2004 detailed phone based interviews were carried out with users who had agreed to trial Weed Manager during the 2003/2004 season. The system was distributed to 50 users, but the final number interviewed was only 18 (7 farmers, 9 consultants and 2 lecturers). However, the participants gave feedback on a range of questions relating to the overall helpfulness and usefulness of the system. They highlighted many specific issues relating to the appearance of the user interface, decisions and the weed and herbicide encyclopaedias, and gave suggestions for improvements. Of the people interviewed, 13 said they would be likely or very likely to use Weed Manager in the future. The reasons behind this included how useful it would be in: supporting complex decision making, planning control strategies, teaching, and dealing with unfamiliar problems that may arise. Most of the users said that the rotational aspect (8/18) or the encyclopaedia (7/18) was the most useful, and many commented that the within season screen was complex. However, when asked which view they would prefer to start with, there was no significant difference: nine preferred within season and eight preferred rotational. The most common negative comments were a lack of confidence or trust in the output from the system (9/18), the time needed to learn and use the system (5/18), the lack of integration with existing crop data management systems (5/18), or the perception that the agronomist does the same job (4/18).

During the 2005–2006 and 2006–2007 seasons, Weed Manager was used by about 100 farmers and advisers. They were asked to provide feedback on the program, and positive comments were received on its ease of use. The users varied in the parts that they used most: rotational, within season or the encyclopaedia.

5.2. Model testing

The models were tested against published data during development and against limited trials conducted within the project. These are described in Benjamin et al. (in press) and Tatnell et al. (2006). Experiments were conducted over two seasons at three sites for three weeds (black-grass, cleavers and chickweed), although not every weed was present at every site. These were used to test the prediction of emergence, growth stage and yield loss by the within season model. The predictions of emergence and development were found to be good. In the first season a very dry autumn resulted in low weed populations with negligible yield loss. In the second season, which included herbicide treatments, the predicted yield losses with uncontrolled or partially controlled black-grass were lower than observed by about half, leading to a recommendation to recalibrate the competitiveness parameter for this weed. The observed density of cleavers was very high, but the resulting yield loss was low, although this

weed is normally highly competitive. A panel of farmers, agronomists and scientists assessed that the predictions of the model were closer to the yield loss that would have been expected from previous trials and field experience. Taking these adjustments into account, the model was able to predict the response to autumn and early spring herbicides, but failed to deal with late spring herbicides, which were beyond the scope of its design.

The rotational model, could not be tested against new trials within the duration of the project, so it was compared with published data, such as Munier-Jolain et al. (2002) for black-grass, Knab & Hurlle (1986) and Zwerger & Hurlle (1990) for chickweed. In general, the model parameters used resulted in slightly lower control of the weed populations than those observed, leading towards risk-averse management strategies, but the pattern of response to different cultivation options was correct.

The available data were not sufficient to test all the species and treatments, so further evaluation of both models was conducted by a panel of experts from within the project. This included members from the south of England and Scotland, providing experience over a range of climatic conditions.

The more formal parts of this testing consisted of defining a set of scenarios and asking the panel for the results they would expect. These were then compared with the results obtained by running the models. For the within season model this was applied to the large scale behaviour, such as the impact on final yield of an initial weed population, and to specific details, such as the expected emergence date of weed species given specific cultivation sequences. For the rotational model, testing concentrated on the dynamics of each species in response to consistent management options. Less formal testing also allowed the experts to run through a larger series of scenarios with the model to identify any anomalous results.

At the end of this process it was agreed that, although the absolute precision of the models in comparison with experimental data was not high, the relative responses to treatments were adequate to allow the formation of suitable weed management strategies. However, there is a need for further calibration of the predictions, especially in the context of the questions of trust raised by the user interviews.

6. Examples

6.1. Weed control within a season

To illustrate the within season models, an example was constructed consisting of winter wheat drilled on 1 October 2006 following harvest of the previous crop on 14 August 2006. The weeds were barren brome at 4–12 plants/m² (low-medium), cleavers at 3–8 plants/m² (low-medium) and herbicide resistant black-grass at 101–250 plants/m² (medium-high). The results are shown in Table 1, where the 16 herbicides provided on the working list are designated by letters A–P. Starting with an inversion tillage plan (mouldboard plough and harrow), which gave a mean margin of £375, the herbicide programme was optimised, resulting in a 2-spray programme with a mean margin of £482/ha. Variations were considered by retaining each of the sprays from the optimum programme individually, both of which reduced the margin considerably. Finally another optimisation was performed, in which the cultivations were included. This resulted in the same herbicide programme, but inversion tillage was replaced by direct drilling, giving a margin of £519/ha. Although the yield was slightly lower, the reduced cultivation cost compensated for this.

Table 1. In season model with barren brome, cleavers and black-grass. Results of optimum and non-optimum spray programmes

Programme	Cultivations	Herbicides ^a	Mean yield, t/ha	Mean margin, £/ha ^b
Optimal cultivations and herbicides	1/10/06 direct drill	B 17/11/06 H 7/2/07	9.3	519
Optimal herbicides after plough	28/9/06 plough 30/9/06 harrow 1/10/06 drill	B 17/11/06 H 7/2/07	9.4	482
Plough, autumn spray	28/9/06 plough 30/9/06 harrow 1/10/06 drill	B 17/11/06	8.3	434
Plough, spring spray	28/9/06 plough 30/9/06 harrow 1/10/06 drill	H 7/2/07	8.1	425
Plough, no sprays	28/9/06 plough 30/9/06 harrow 1/10/06 drill		7.0	375

a Sixteen herbicides denoted A–P were available for optimisation

b Margins are based on prices for the 2005–06 season

6.2. Weed control over a rotation

Tables 2–5 illustrate the results of the rotation model. A base case was set up as shown in Table 2, using a rotation of 2 years winter wheat, winter oilseed rape, 2 years winter wheat, winter beans, and with a mixture of cultivations, moderate herbicide costs and mid sowing dates. The weeds considered were black-grass with herbicide resistance and barren brome. The initial plant densities were set to give moderate seedbanks. Note that the first column of the table shows the results at the end of the first season, when the seedbanks had increased. The range in margin due to the variability in the weed population (see section 4.3) was £0–303/ha with a mean of £152/ha, and the weed seedbank was higher at the end than the start. Table 3 shows the results of optimising this system. The sowing date was changed to late in every year, non-inversion tillage was replaced by ploughing, and the herbicide cost on the wheat, but not the break crops, was increased. The expected margin was £246/ha, with much less variability. The barren brome seedbank was well controlled, and the black-grass fairly well. Note that the optimisation begins in the second season; the first is unchanged because it represents the current season in which most of the decisions have already been taken. Late sowing was recommended throughout the optimised plan, to reduce the amount of black-grass emerging in the crop, but it would be problematic for the farmer to adopt such a strategy across the whole farm, because inclement weather could prevent late sowing. However, it does highlight that fields with this particular weed problem should be sown last when planning the timing of autumn sowing of winter wheat.

Table 4 shows a slightly revised base case in which the break crop in year 3 was changed from winter to spring oilseed rape. This gave good control of the barren brome population in that year, and improved the control of black-grass, but the black-grass population recovered rapidly due to seed rain and seeds ploughed from the deep layer. The expected margin was £158/ha, slightly better than without the spring crop, because the margins following the break crop had improved. Table 5 shows the result of optimising this system. The changes were similar to those in the original base case, except for the change to non-inversion cultivation for the break crop and the following year. The expected margin over the rotation was

£241/ha, which was slightly less than when using winter oilseed rape in year 3. Looking at the individual years, the margins of all the crops following the break had increased, but the margin for the break crop itself was lower than for the winter break crop, because the maximum weed-free yield was lower. The most significant difference was the improvement in the control of the black-grass population.

As noted in section 5.2, the management of the black-grass population was generally slightly more cautious than would be required on the basis of Munier-Jolain et al. (2002). The use of ploughing to control barren brome is well-established (Peters et al., 1993; Smith et al. 1999), as is the effectiveness of a spring crop.

Table 2. Rotation model example with winter cropping before optimisation

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 ^a						
Black-grass (resistant)	High	Very high	High	Very high	Very high	Very high
Brome: barren	High	Very high	Moderate-high	Moderate-high	Very high	High
Margin (£/ha) ^b	259	140	160	190	148	14
Average margin over rotation £152/ha (0-303)						

a Densities at the start of the first season were moderate

b Margins are based on prices for the 2005–06 season

Table 3. Rotation model example with winter cropping after optimisation

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 ^a						
Black-grass (resistant)	High	Low-Moderate	Moderate-high	Low-moderate	Low-moderate	Low-moderate
Brome: barren	High	Low-moderate	Low	Very low	Very low	Very low
Margin (£/ha) ^b	259	307	194	320	322	72
Average margin over rotation £246/ha (209-283)						

a Densities at the start of the first season were moderate

b Margins are based on prices for the 2005–06 season

Table 4. Rotation model example including a spring crop before optimisation

Season	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011
Crop	Winter wheat	Winter wheat	Spring 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 - 75	40 - 75	40 - 75	40 - 65
Number of seeds in the shallow soil layer at the end of the season ^a						
Black-grass (resistant)	High	Very high	Low	Very high	Very high	High
Brome: barren	High	Very high	Very low	Very low	Low-moderate	Low
Margin (£/ha) ^b	259	140	86	199	222	43
Average margin over rotation £158/ha (35-281)						

a Densities at the start of the first season were moderate

b Margins are based on prices for the 2005–06 season

Table 5. Rotation model example including a spring crop after optimisation

Season	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011
Crop	Winter wheat	Winter wheat	Spring oilseed rape	Winter wheat	Winter wheat	Winter beans
Cultivation	Plough	Plough	Non-inversion	Non-inversion	Plough	Plough
Sown	Mid	Late	Late	Late	Late	Late
Cost (£/ha)	40 - 75	75 - 105	< 40	75 - 105	75 - 105	40 - 65
Number of seeds in the shallow soil layer at the end of the season ^a						
Black-grass (resistant)	High	Low-moderate	Low	Low-moderate	Low	Low
Brome: barren	High	Low-moderate	Very low	Very low	Very low	Very low
Margin (£/ha) ^b	259	307	134	337	331	77
Average margin over rotation £241/ha (211-270)						

a Densities at the start of the first season were moderate or moderate

b Margins are based on prices for the 2005–06 season

7. Conclusions and future directions

Weed manager has been developed, tested and shown to have the potential to assist weed management decision in winter wheat and arable rotations. However, quantitative testing of the models, particularly for some of the less studied weeds, has been limited by the availability of data, so further validation and calibration of the models, and further testing of the decisions in practice is still needed.

Weed Manager could be expanded in several directions in future. First, the number of weed species needs to be increased by creating suitable parameter sets. Second, extending the crop model to other cereals and developing models for other types of crops, such as oilseed rape and legumes, would lead to its use in more arable cropping situations. Third, the outputs and optimisation options could be extended to include biodiversity decisions and other environmental impacts. Beneficial weeds are already identified by the environmental icons, so maintaining them within a crop or headland could be an objective. The choice of

herbicides may be restricted in specific environmental sensitive catchments because of the potential for certain chemicals to exceed Environmental Quality Standards (EQS), and Weed Manager could be used to propose strategies for weed control with a reduced risk of environmental harm.

8. Acknowledgements

This project was sponsored by Defra through the Sustainable Arable LINK programme (LK 0916). The industrial funders were HGCA (Project Number 2286), BASF, Bayer CropScience, Dow AgroSciences, DuPont and Syngenta Crop Protection UK Ltd. The research partners were ADAS, Rothamsted Research, Silsoe Research Institute, the Scottish Agricultural College and Glasgow Caledonian University.

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