Development and validation of 'Weed Management Support System' (Weed Manager)

by

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6.0 APPENDICES

*Appendix L is available electronically on the HGCA website, and does not form part of the printed report.

ABSTRACT

The aim of this project was to develop and validate 'Weed Manager', a computer-based Decision Support System module designed to fit within the Arable Decision Support suite of modules to provide farmers, agronomists and distributors with a robust tool to plan and develop weed management strategies.

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 a six-year arable cropping period. Both parts are model based, using data specific to individual farms. The critical objective was to predict the impact of an actual or anticipated weed population on the yield of winter wheat and to investigate a range of mitigation strategies (crop agronomy, weed control options) to reduce or prevent yield loss. Each management option is ranked economically for the user to compare and select. The complex models behind Weed Manager are fully functioning for 13 common arable weed species, including the major UK weeds such as black-grass, chickweed, cleavers and wild-oats. The involvement of intended users via workshops, surveys and events during the development phase (2000-2005) ensured that it is a user-friendly weed management tool.

Additional features of Weed Manager are the herbicide and weed encyclopaedias. There is a comprehensive herbicide database and encyclopaedia containing information on approximately 150 herbicides used in winter wheat. Herbicide data for 20 rarer or more unusual weed species for which data were not previously available were generated through a set of glasshouse screening trials. These results are displayed as additional information in both encyclopaedias. The weeds encyclopaedia also contains detailed information on the weed biology, life cycle, geographic location, environmental effects, identification of, and control measures for, over 140 key arable weed species, along with photographs of all the key growth stages from cotyledon through to flowering. Both encyclopaedias display data used in the decision support part of the system, or can be accessed and used separately. Additional information on specific issues such as herbicide resistance, environmental impacts, biodiversity and cultural control measures are all included.

Weed Manager is now available on CD by contacting WeedManager@adas.co.uk.

SUMMARY

The aim of the Weed Management Support System (WMSS) project was to produce a usable and robust decision support system to improve weed management in winter wheat, while promoting environmentally-sound decision making, enhancing crop profitability and the biodiversity of farmland. The WMSS is now known as Weed Manager and is a computer-based Decision Support System module designed to fit alongside the Arable Decision Support (ArableDS) suite of modules and has been commercially available from July 2005.

Weed Manager is one of a range of decision support tools that use the same pesticide, basic agronomic, weather and user farm data; operate within the data sharing environment (DSE) software and have common user interface elements to help users in learning to use the system. Weed Manager provides farmers, agronomists and distributors with a robust tool to plan and develop weed management strategies. 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 a six-year arable cropping period. Both parts of the system are model based, using data specific to individual farms.

The project was managed by dividing it into a number of different working groups defined by the specific skills required, and each one was led by individual organisations. The groups were: System Development (Rothamsted), Decision Modelling (SRI), Biological Models (Rothamsted), Weed Biology (ADAS), Herbicides (SAC) and Dissemination (ADAS). Each of these working groups met every 2 months through the 5 years of the project, which ensured that the project was kept on track and met the required milestones. In addition to these working groups a Herbicide Steering Group (led by SAC) and Dissemination Group (led by ADAS) were set up and information from these groups were fed into the biennial Project Management Group meetings involving the whole project consortium.

In order to ensure Weed Manager was a user-friendly system, users (farmers, agronomists and distributors) were involved through all stages of the project, from interface design to testing the decision-making processes.   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 workshops held at various locations in England and Scotland. A number of key points were highlighted from these early consultations that helped to focus development. These included: easy data entry and links to other systems; provision of mechanisms to intervene and override

initial default values; understanding and confidence in system assumptions; ability to optimise and compare future strategies and manage herbicide resistance in tactical and strategic decisions. Additional user involvement included a postal survey, email consultations and detailed telephone interviews towards the end of the development phase (March to October 2004).

The user interface displays the two different types of decision tools in the Weed Manager system: within-season and rotational management decisions. The user can rapidly switch between these two different aspects of the program which are referred to as *views*. Each shows the same weed spectrum, while the management decisions of the within-season module are shown in the first year of the rotational view. Each view is linked to a biological model and a decision model.

The pesticide data that are used in Weed Manager are provided by the DSE which contains statutory herbicide information (from the LIAISON database developed by Central Science Laboratory, York) and data provided by the collaborating chemical companies on efficacy and tank mix information on their specific products. These data are used by the decision support process models to calculate the expected outcomes, which are then displayed to the user on the within-season interface. Basic agronomic data are used to provide default values for drilling and harvest date, crop value, basic cultivation and spray costs, as well as values for variable costs associated with each crop. The system uses local weather data specific to each site and this can be downloaded from the ArableDS web site, with over 100 possible weather sites available. The data are stored in a large access database and are effectively hidden behind the user interface.

A critical objective of Weed Manager was to predict the impact of an actual or anticipated weed population on the yield of winter wheat and then to determine how yield loss can be mitigated by alternative management strategies (crop agronomy, weed control). The outcome of the biological model of weed competition would then be used within the decision model to select and rank economically optimum solutions. In addition, Weed Manager was designed to provide information and advice on strategic management of weed populations over several years in a crop rotation. Unlike most other plant protection decisions, the consequences of weed management can persist for many seasons. 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. Weed Manager contains full sets of parameters for the major UK arable weeds (e.g. black-grass, wild-oats, cleavers

chickweed), but the current version only includes a total of 13 species. Herbicide-resistant and susceptible biotypes of grass and broad-leaved weeds are treated separately.

The user can propose a range of cultural practices, rotations and weed control options and the system will calculate the yield losses and economic consequences for a single season or through a rotation. Alternatively, they can use the decision part of the system. The within-season decision model is used when the user selects the '*suggest treatments*' action from the within-season view in Weed Manager. The objective is to suggest a range of different herbicide and cultivation plans that are then ranked by gross margin for the current season, based on the previous season's harvest date and a fixed sowing date. The margin used is the value of the grain less the herbicide and cultivation costs. The rotational decision model is used when the user chooses the '*suggest treatments*' command from the rotational 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 weed management strategy throughout a defined rotation of up to 6 years.

Additional features of Weed Manager, that have proved to be extremely popular with the users, are the herbicide and weed encyclopaedias. There is a comprehensive herbicide database and encyclopaedia containing information on approximately 150 herbicides used in winter wheat. Herbicide data for 20 rarer or more unusual weed species where data were not previously available have been generated through a set of glasshouse screening trials that were carried out at ADAS and SAC. These results are displayed in the system as additional information in both encyclopaedias. The weeds encyclopaedia also contains detailed information on the weed biology, life cycle, geographic location, environmental effects, identification of and control measures for over 140 key arable weed species, along with photographs of all the key growth stages from cotyledon through to flowering. Both of these encyclopaedias display data used in the decision support part of the system, or can be accessed and used separately.

Validation of the system has taken place at all stages of development, including data checking of data entry by experts and validation of system output by weed experts. In addition, a set of field trials were established in 2002/03 and 2003/04, covering three different geographical locations and three common weed species (black-grass, chickweed and cleavers). The trials included a range of weed densities, timings of herbicide applications and a range of herbicide products and included plant counts and final yield assessments. These data were then evaluated against the outputs from the models.

Detailed phone-based interviews were carried in the last year of the system development with farmers and consultants who had previously agreed to trial Weed Manager during the 2003/04 season. The system was distributed to 50 users, but despite extensive efforts being made to contact all of these people, only 18 of these were finally interviewed. However, excellent feedback was received on a range of questions relating to the overall helpfulness and usefulness of the system and many specific issues relating to the appearance of the screens, decisions and the weed and herbicide encyclopaedias, with useful recommendations highlighted. From the responses received, 72% of people said they would be likely or very likely to use Weed Manager in the future. Some negative comments were made. These usually included a lack of confidence or trust in the output, the time taken to use the system, the lack of integration with current crop data management systems (eg. Muddy Boots), and the perception that the agronomist can more effectively do the same job. The overall message from the user survey showed that Weed Manager, along with the other ArableDS modules are going in the right direction, but the lack of trust and understanding of the potential benefits are hindering the uptake further.

In the first four years of the project various dissemination options were considered. The conclusion was that Weed Manager should be released as part of the ArableDS suite. The major reasons for this included the fact that: non-specific updating costs, i.e. weather, pesticide data and general information could be shared; support and help would be available; the databases, browser and interface existed already; farm information could be input to a central store for all modules.

The first version of Weed Manager is now available on a CD by contacting WeedManager@adas.co.uk. By the end of September 2005 there were more than 50 users of Weed Manager, including Farmers, advisors, academics and other industry users.

TECHNICAL REPORT

1.0 INTRODUCTION - DEVELOPMENT OF 'WEED MANAGER'

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 such practices are required.

Computer-based Decision Support Systems have been in development in many countries around the world for the last decade, once increases in computer power made such computer resource hungry systems feasible. Some of these have been developed by weed biologists and thus have a biology emphasis (e.g. Renner *et al*., 1999; Berti *et al*., 2003) whilst others stem from a more pesticide oriented origin and focus on herbicide selection (e.g. Kudsk, 1999). The aim of this project was to endeavour to combine both elements into a system that would assist the choice of herbicide products and explore the biological/agronomic consequences of such choices through a rotation.

Weed Manager is a computer-based Decision Support System module designed to fit within the ArableDS suite of modules. It provides farmers, agronomists and distributors with a robust tool to plan and develop weed management strategies. 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 a six-year period of an arable rotation. Both of these parts of the system are model based, using data specific to individual farms. There is a comprehensive herbicide database and encyclopaedia within the system, containing information on approximately 150 herbicides used in winter wheat. The weeds encyclopaedia contains detailed information on the weed biology, life cycle, geographic location, identification of 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. Weed Manager contains a full 'Help' system to guide the user when required.

In order to ensure Weed Manager was a user-friendly system it has been developed by involving Users (farmers, agronomists and distributors) at all stages of the project, from interface design features through to testing the decision making processes.

Weed Manager was developed using user-centred design. It operates within the ArableDS data sharing environment (DSE). The DSE provides a toolkit of components to facilitate development of decisions support modules. These components give access to pesticide, basic agronomic, weather and user farm data as well as providing common user interface elements which help users in learning to use the system (DESSAC final report, 2000; Parsons *et al.,* 2004 & Defra AR0915 Final report).

The following report includes a summary of all aspects of the development of Weed Manager, from initial user consultation through to the system launch in July 2005. The full details of many of the models and the methodology of the validation trials are located in appendices.

1.1 User Input

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 (Summary in Appendix L, section 1.0). These included:

- easy data entry and links to other systems; to intervene and override initial default values
- understanding and confidence in system assumptions
- optimise and compare future strategies
- manage herbicide resistance in tactical and strategic decisions

A valuable group of users was established and consulted during the project. Despite problems at the early stages with recruiting and maintaining numbers (Parker, Park & Ginsberg, 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 farmers and consultants who had previously agreed to trial Weed Manager (Version 2Ua) during the 2003/04 season (The full details of the final questionnaire results and conclusions are summarised in Appendix L, section 3.0). The system was distributed to 50 users, but despite extensive efforts being made to contact all of these people the final number interviewed was only 18 (7 farmers; 9 consultants; 2 lecturers). However, excellent feedback was received on a range of questions relating to the overall helpfulness and usefulness of the system and many specific issues relating to the appearance of the user interface, decisions and the weed and herbicide encyclopaedias, with useful recommendations highlighted. From the responses received 72% of people 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, strategically planning control strategies, teaching, or dealing with unfamiliar problems that may arise. In particular the rotational aspect of the system and the weed encyclopaedia were considered to be extremely informative and of great value to the user. Where negative comments were made they usually included a lack of confidence or trust in the output from the system, the time aspects of using the system, the lack of integration with existing crop data management systems (eg. Muddy Boots), or the perception that the agronomist does the same job.

The overall message from the user survey showed that Weed Manager, along with the other ArableDS modules are going in the right direction, but the lack of trust and understanding of the potential benefits are hindering the uptake further. These comments were carefully considered and during the remaining months of the system development and through careful publicity to increase the public awareness of how the system functioned and the potential benefits these issues were addressed.

1.2 System structure

The outline structure of the system is shown in Fig. 1. All the data are stored in MS Access databases. The encyclopaedia is displayed in the Rothamsted browser (Castells-Brooke *et al.,* 1999), which uses the Microsoft Web Browser component to display the encyclopaedia pages. The encyclopaedia is described in detail in (Appendix C). 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 can be developed on multiple sites. The module is described in more detail in the system architecture summary in Appendix G.
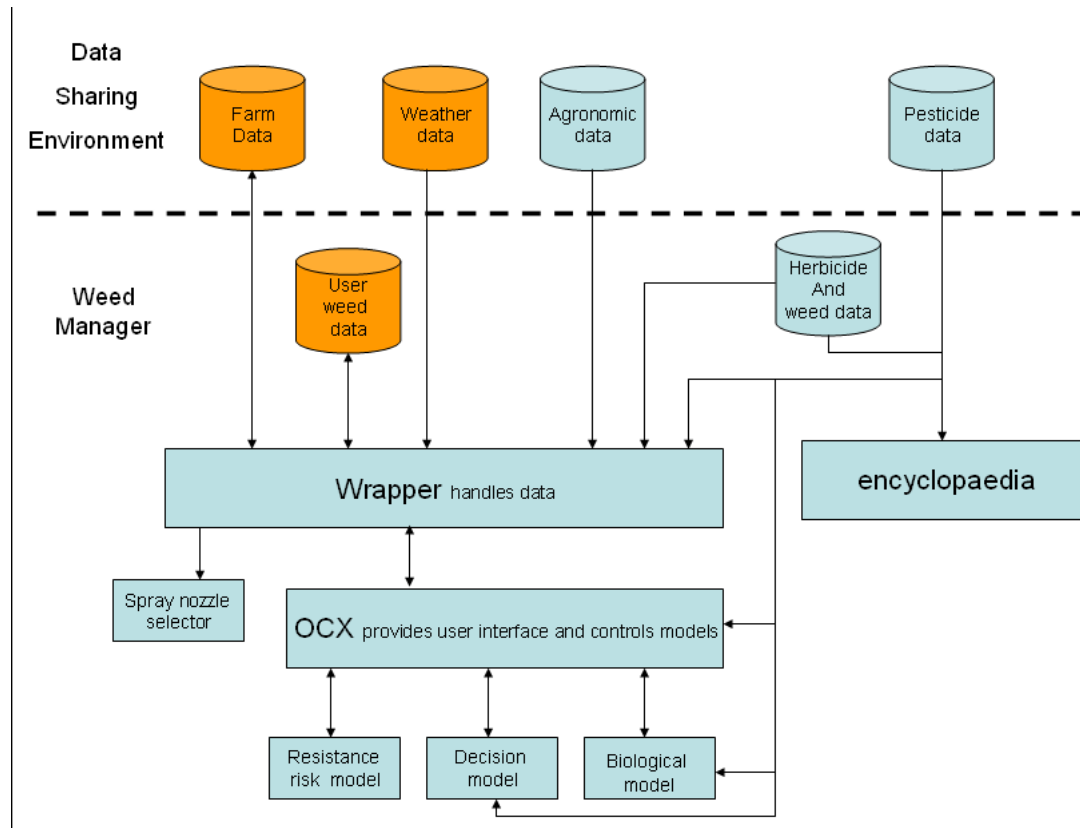
Fig. 1 The outline structure of the Weed Manager system.

1.3 User interface

As described earlier, Weed Manager has been designed to support two types of decisions: within-season decisions on the control of weeds in a single winter wheat crop (***within-season***), and rotational management decisions that consider strategies for weed control over several years (***rotational***). The two aspects of the program are referred to as *views*, and the user can rapidly switch between them by clicking a button on the toolbar. The first year of the rotational view always shows the same weed management decisions as the within-season view. Each view is linked to a biological model and a decision model, which are described below.

1.3.1 The within-season view
The within-season view is displayed when starting Weed Manager. However, the first time the system is used for a new farm, the list of weeds to be considered has to be set up. This is

done through the *weed list editor*, which is presented to the user automatically (Fig. 2). At this point, the weeds of interest and estimates of their expected density in the crop, in terms of one of 4 density bands, are selected (see section 3.5). After saving the list, the program proceeds to the within-season view. It is possible to return to the weed list editor at any time.
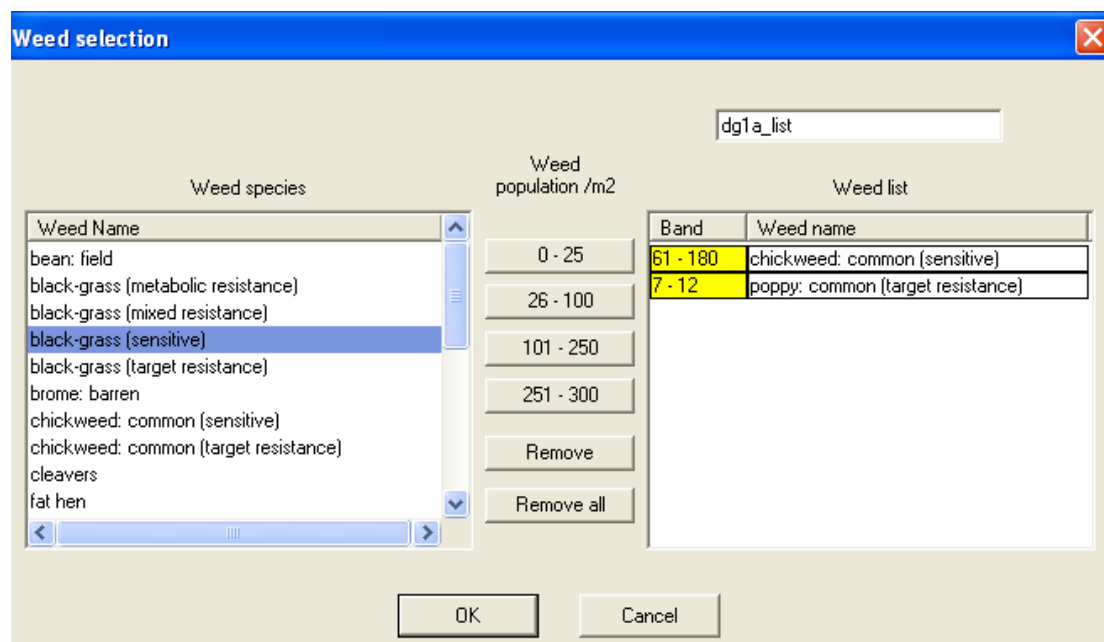
Fig. 2 The weed list editor

The within-season view can be used prior to sowing or at the time a weed problem is evident in a field of winter wheat. This can be at any time from just after harvest of one crop to the harvest of the next crop. The screen layout shares many features with other ArableDS programs, which makes it easier for users to learn (Fig. 3). Below the usual menu and toolbars, there is an information bar showing basic details of the field crop and key dates. Clicking on the buttons next to them can edit all these.

The main area of the screen shows 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 temporal 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 wheat 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 to show a different range of dates, or zoomed in and out to concentrate on a particular period.

Additional information on each weed is provided down the left of the screen. Up to 3 icons (from a total of 8 icons, see section 5) 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 and the yield loss resulting from the weed population. On the far right of the screen another vertical bar shows the estimated yield (t/ha) or economic margin and the degree of uncertainty in the estimates.
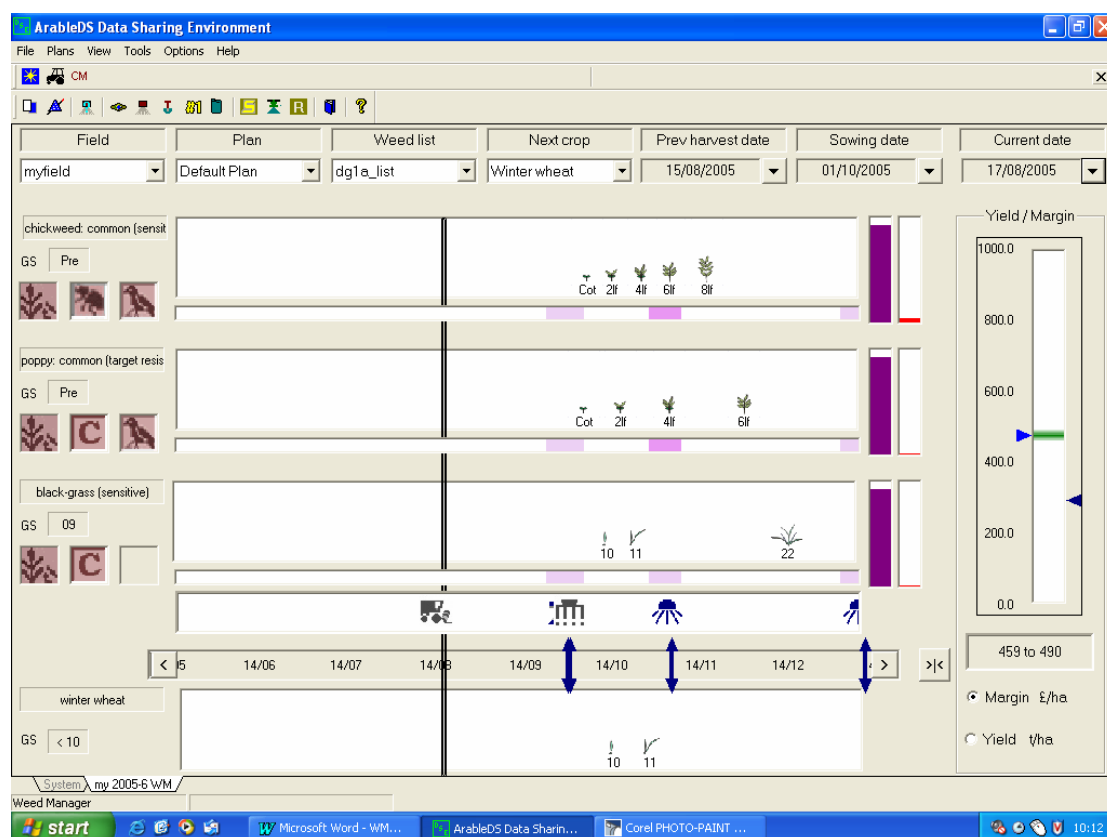
Fig. 3 The within-season view

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 actions from the menu. These present similar dialogs showing the current plan on the right and the available cultivations or herbicides on the left. Operations can be added on any date or removed from the plan. In the case of herbicides, the required dose can also be chosen from the ones available. To reduce the need to select from a long list of all the available herbicides, the *chemical list editor* should be used to create a short list of products that will be displayed.

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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, to make them more accurate.

The within-season module can be run at any time by selecting the current date from the date button. 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 gross 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 the *suggest treatments* feature. Provided that a chemical list of fifty products or fewer has been selected, this will 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 the section on the decision model for management of weeds within a season (section1.5). Having obtained a list of management programmes, one can then be selected for more detailed examination in the main view.

The menu and tool bar also provides access to the herbicide resistance module (see Appendix H) and the spray nozzle selection module (See Appendix K).

1.3.2 The rotational view

The rotational view allows the consequences of weed control decisions to be examined over a 6-year rotation. 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 provided by most of the other ArableDS programs, because they focus on single-season decisions (Fig. 4).
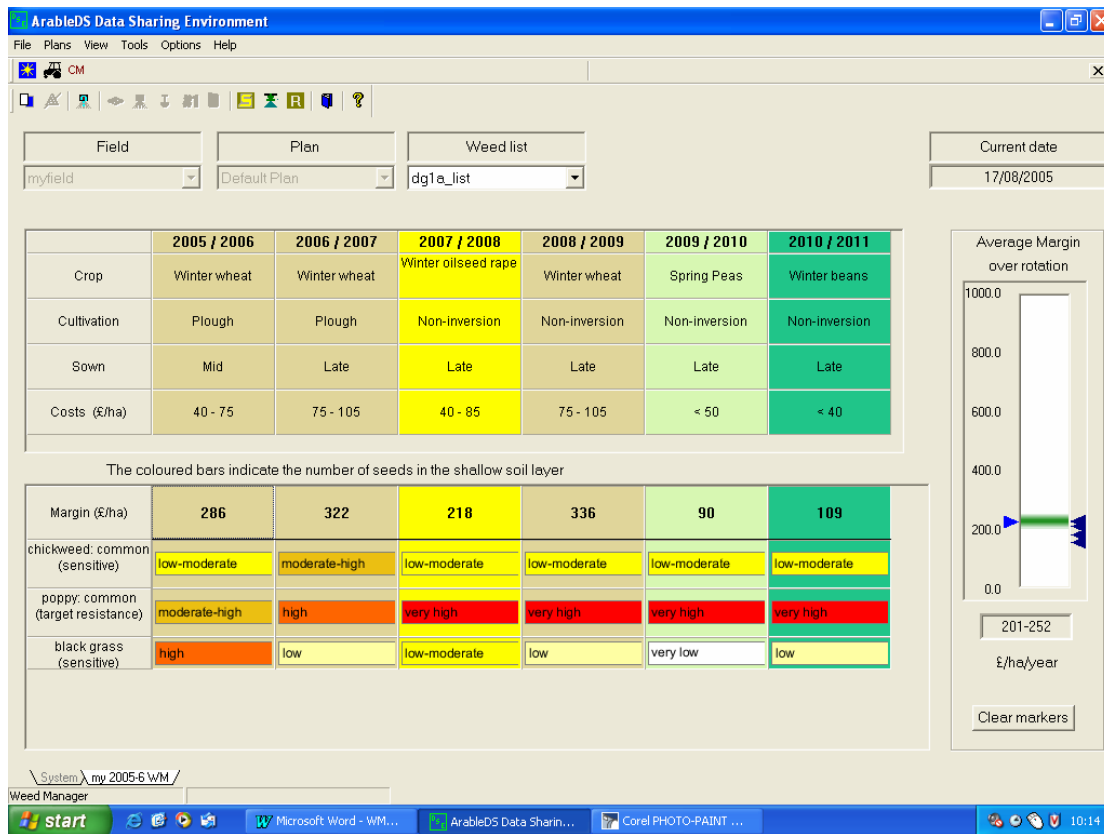
Fig. 4 The Rotational view

A grid occupies most of the screen 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 4 bands). The user defines the possible crops that could be grown on the field at the outset. Other than the crop and cultivation for the first year, which are fixed, any of the other pieces of information can be changed directly by right clicking on the grid cell. The results of changes are recalculated immediately and redisplayed.

The lower part of the screen shows the results of the model. The biological model (described below) 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 seed population. 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 *suggest treatments*. In this case the user can choose how many years, up to 5, to include in the rotation. The decision model for management of weeds in a rotation finds the optimum strategy consisting of cultivation type, sowing date and herbicide cost for the whole rotation and presents it on the screen.

During the final year of the project a detailed examination of the user interface (heuristic examination) was carried out by Caroline Park of Glasgow Caledonian University (Appendix L) where design issues were highlighted and addressed.

1.4 Biological models

1.4.1 The biological model of weed population dynamics within a season

A critical objective of Weed Manager is to predict the impact of an actual or anticipated weed population on the yield of winter wheat and then to determine how yield loss can be mitigated by alternative management strategies (crop agronomy, weed control). The outcome of the biological model of weed competition is then used within the decision model to select and rank near-optimal solutions on the basis of margin.

The biological models have been fully parameterised for thirteen major weed species: black-grass, barren brome, common chickweed, cleavers, fat hen, knotgrass, annual meadow-grass, common poppy, Italian ryegrass, wild-oat and the two broad-leaved crop volunteers, oilseed rape and field beans. Additionally, for black-grass, Italian ryegrass, wild-oat, common poppy and common chickweed, the models will differentiate between populations with target site or metabolic herbicide resistance, or those with a combination of the two.

The basic question addressed within the consortium at the outset of the project was whether to base prediction of weed competition on weed density or on relative leaf area of crop and weed. Theoretically, the latter is more likely to be accurate, as it takes into account variability in emergence dates between crop and weeds, thus accounting for differences in sizes of weeds. Thus, a decision was reached essentially to base the yield loss predictions on relative leaf area. In practice, the users are not in a position to actually measure crop and weed leaf area, therefore the system requires farmers to indicate the weed density present or anticipated. The plants/m^2 are converted within the model to leaf area, depending on the estimated emergence dates of crop and weed (see below). The system will also convert ground cover assessments to leaf area, provided the weed cover is relatively low. In practice it has been

found that variability in assessing leaf areas makes predictive models based on leaf areas hardly more reliable than density models (Cussans, 2005, pers. comm.).

Although the biological models will function with a continuum of weed densities of $1 - n$, it is not realistic for users to input precise density information on the weed infestations present in a given field. This is mainly due to the time involved in collecting such information and because of the intrinsic variability of densities within a field. However, it was felt that it was appropriate for users to identify the approximate densities, on the basis that 'this field has a bad infestation' of one weed and a 'light infestation' of another. Consequently, each weed has been allocated four density bands, ranging across the spectrum of yield responses from virtually uncompetitive infestations through to highly competitive ones. The bands for each species were established independently, but species of similar competitive ability tend to have similar bands (Table 1).

Table 1 Density bands (plants/m^2) used in Weed Manager for estimating yield losses

Weed species	Low	Medium	Medium/High	High
Beans	0-2	3-8	9-24	25+ (74)*
Black-grass	0-25	26-100	101-250	250+ (300)
Barren brome	0-3	4-12	13-48	49+ (98)
Common chickweed	0-15	16-60	61-180	181+ (230)
Cleavers	0-2	3-8	9-24	25+ (74)
Fat hen	0-3	4-12	13-48	49+ (98)
Knotgrass	0-3	4-12	13-48	49+ (98)
Annual meadow-grass	0-25	26-100	101-250	251+ (300)
Oilseed rape	0-3	4-12	13-48	49+ (98)
Common field poppy	0-3	4-6	7-12	13+ (62)
Italian ryegrass	0-10	11-40	41-120	121+ (170)
Wild-oat	0-3	4-12	13-48	49+ (98)

* for modelling purposes the number in brackets is taken as the upper limit

One of the key elements of Weed Manager is to act as a strategic tool so that the user can explore the likely impact of different cultural practices (cultivations, sowing dates) and weed control treatments on crop yields and profitability. The user can input anticipated weed infestation levels and the models will predict their emergence and competitive impact. As a result the system has to model emergence patterns of the crop and weed driven by the

biological characteristics of the species, the weather (temperature and rainfall) and cultural practices.

Finally, the information on the emergence and growth of crop and weeds is converted into anticipated growth stages which are presented visually to users and also drive the selection of herbicide products, as the activity of herbicides varies with the size and growth stage of the target weeds.

1.4.1.1 Description of the Within-season Model

Climate and Astronomical Data

The model determines day length depending on time of year and latitude. Weather data such as maximum and minimum temperatures, rainfall, radiation and evapo-transpiration have been collated from a range of sites in the United Kingdom. Users can use the site closest to their farm/field as a source of this information, but they can also import their own weather data, if they have it available.

Seedling emergence

Intrinsic biological characteristics of weed species can restrict their emergence to certain times of the year. Thus, some emerge in autumn, others in spring and others have no particular seasonality (as do crops). Published emergence patterns for weeds (eg Naylor, 2002) have been incorporated into the within-season model so that if a crop is established at a particular date, only those species with an emergence pattern that permits emergence at that time of the year will be activated. For each species the numbers establishing each month are expressed as a proportion of the maximum number of seedlings emerging in the year. This number depends on the dormancy pattern of the species, plus seed germination rate, and on the soil water potential and the temperature. The weather data has to be included, as if the soil is too dry or the temperatures too low the seeds will not germinate even though they are physiologically able to do so. Temperature also drives the rate of emergence. In order to accommodate constraints imposed by the computing requirements of the decision model of Weed Manager some simplification of the emergence behaviour has been introduced. Each weed species emerges as eight equal cohorts. Seven of these start emerging in the autumn, depending on the seasonality of the weed species, once the previous crop has been harvested and soil moisture levels are high enough to permit germination. Emergence of the eighth cohort is initiated by soil cultivation associated with crop drilling. This accommodates the known impact of soil cultivations on stimulating weed emergence.

The system assumes two basic types of cultivation, non-inversion and ploughing. The former leaves the seeds shed in the previous year in the top 10cm of soil, where they are available to germinate and so seedling emergence is linked to the timing of the harvest of the previous crop (as outlined above). However, ploughing is assumed to bury the majority of seeds present on the soil surface and introduces a new (older aged) population of seeds from the deeper seedbank to provide the basis for future seedlings. Consequently, calculations of emergence of seedlings, where ploughing is the primary cultivation, are initiated at the date of ploughing.

Phenology-development of crop and weeds

As explained earlier, the decision models need information on the growth stage of crop and weed, as these impact on herbicide choice. For graminaceous weeds the standard decimal growth stage code for wheat was adopted (Zadoks *et al..,* 1974). Leaf, tiller, node and ear development has been associated with the temperature and day-length, based on a previously established model of Milne *et al.,* (2003). A similar approach is taken for broad-leaved weeds except that the number of stages calculated is smaller. The growth stage of the most precocious cohort is used within the decision model and is presented to users on the 'within-season' screen (Fig. 3).

Crop Yield Loss

The estimation of crop yield loss is based on a combination of an ecophysiological model that predicts the early growth of wheat and weeds, combined with a simple empirical yield loss equation. The growth of each weed species in the community from emergence to canopy closure is simulated using an ecophysiological model (Kropff & van Laar, 1993). The initial green area of each cohort of weeds and wheat is 'grown', primarily based on the attributes of the species and the temperature, until the total green area index (GAI) reaches 0.75, which is taken as the point of canopy closure. Yield loss from each species is predicted from the relative proportions of the crop and weed leaf area, according to the model of Kropff *et al.,* (1995). The yield loss from each species depends on the relative green leaf area at canopy closure and the competitive ability of the species defined as the damage coefficient (*q*). Yield losses from several species are summed, assuming no interspecific competition. Although this is not scientifically accurate, it is an adequate approximation, since most weed populations will not be in the very high category, where such competition could be important.

Weed control measures

Both herbicide treatments and mechanical weed control (e.g. tine weeding) are treated similarly. They are both assumed to destroy a proportion of the green area of the weeds with

an efficacy that varies with the species, the product/method used and the weed growth stage. Each weed species, growth stage and product combination has been assigned a level of weed kill varying from 91% for weeds susceptible to a treatment down to 1% for weeds resistant to a particular treatment. If a sequence of operations is proposed the model calculates the consequences using a multiplicative survival method. The reduction in leaf area of the weeds is then fed into the yield loss model and the reduction in yield loss calculated. In order to simplify the computation of yield losses the model assumes that the reduction in green area is effective at canopy closure and therefore does not include elements associated with effects of the timing of control on the yield loss incurred. It was felt that for most weed treatments in autumn and early spring this was an acceptable approximation.

Observations

The core calculations of this biological model have assumed that the user is using Weed Manager as a strategic tool prior to sowing the winter wheat. The user simply inputs the weed density anticipated. It can also be used once the crop has been sown. Using the observation dialogue the user can input weed densities or weed ground cover, and alter predicted growth stages. This information is used to refine the model predictions to date and for the rest of the season.

Outputs from the model

The fundamental output from the model is the yield loss caused by the weed(s) present. This is then given a financial value based on the value of the crop and the anticipated weed free yield (information provided by the user). The financial loss is balanced by the costs incurred in preventing that loss by controlling the weeds. These costs include cultivation and establishment costs, and herbicide plus application costs. The balance between costs and benefits of control is used in the optimisation programme to select the most cost-effective treatment.

The impact of the weeds on crop yield is changed by a wide range of factors, as outlined above, that influence the time and periodicity of emergence of the weeds, the time of emergence of the crop, the vigour of the weeds and the crop and the performance of weed control techniques (herbicides and mechanical weeding). The user can change the following factors:

1. weed species and infestation band
2. time of previous crop harvest
3. average climate data (depending on year and location in the UK)
4. date and type of primary and secondary cultivation

5. crop drilling date and density

6. date of weed control treatment

7. type of weed control treatment (primarily herbicide choice)

8. maximum anticipated weed free yields (t/ha)

9. price of wheat (£/t)

Some of these factors (e.g. crop harvest date, crop price, crop density) are set as 'default values' by the system unless the user changes them, but the system will initially assume no weed control treatments have been applied. This provides information on the competitive impact of the weed under the infestation level, cultivation, sowing date and weather conditions provided by the user.

1.4.1.2 Examples of outputs from Weed Manager - Within-season Model

Comparison of twelve weeds with contrasting primary cultivations
These data show the differences in the competitive impact of the twelve weeds, with the two primarily spring emerging and frost sensitive species (fat hen, knotgrass) having no effects on yield and the most competitive species (cleavers) reducing yields to less than 2 t/ha (Table 2). Densities causing maximum yield loss plus densities that are approximately equivalent over all twelve species are presented. The primary cultivation used can influence the emergence of the weed and thus its competitive effect. Barren brome, that has very little dormancy and emerges rapidly, is more competitive in the non-ploughed crop. It is very important to realise that cultivations do not change the weed infestation (weed plant density) as the user is in this situation stating that he/she is expecting the defined infestation level as a result of the proposed cultivation practice. This potential confusion does not arise if the user is providing information about a crop that has already been planted and the weeds have emerged.

Table 2 Modelled yield losses by the 12 weed species following ploughing or heavy discs as the primary cultivation, in the absence of weed control.

(Bedford weather, primary cultivation 15 September, sowing date 1 October, weed-free yield 10 t/ha, crop density 150-199 plants per m^2).

Weed species	Mean density (plants/m^2)*	Yields (t/ha)	
		Plough	Heavy discs
Beans	50	8.1	8.2
Black-grass	275	6.0	5.9
	63	8.1	8.0
Barren brome	74	5.8	4.8
	30	7.0	6.0
Common chickweed	205	7.3	7.4
	38	8.8	8.8
Cleavers	50	1.8	1.5
Fat hen	74	10.0	10.0
Knotgrass	74	9.9	9.9
Annual meadow-grass	275	8.0	8.9
	63	9.1	9.5
Oilseed rape	74	6.0	5.8
Common field poppy	37	8.4	8.3
Italian ryegrass	145	4.6	4.5
	25	7.2	7.0
Wild-oat	74	4.5	3.8
	30	6.6	6.0

* *Densities presented are the mean values of the relevant density bands (Table 1)*

Table 3 Comparison of the effects of weather/climate/location on the competitive effects of weeds, as reflected in wheat yields (t/ha): a) Bedford and b) Leeming weather (*weed free yield = 10 t/ha*)

Weed species	Mean density (plants/m^2)	Bedford		Leeming	
		Plough	Heavy discs	Plough	Heavy discs
Black-grass	275	6.0	5.9	5.6	6.3
Barren brome	74	5.8	4.8	4.2	3.3
Common chickweed	205	7.3	7.4	6	6.3
Cleavers	50	1.8	1.5	2.1	1.1

Comparison of the effects of climate/location

Table 3 compares the effects of location (Bedford in Southern England, with Leeming in Northeast England) in the UK on weed competition, as represented by crop yield loss. Location (latitude) affects day length and thus the amount of sunshine the plants receive but more importantly the weather is different in different part of the UK. As can be been seen (Table 3) yield losses were predicted to be consistently greater at Leeming. Temperature and

rainfall primarily drive these competition effects, but as rainfall was adequate at both sites (Fig. 5) this was probably not a critical factor. As the model uses a higher base temperature for wheat than most weeds, the crop is more sensitive to difference in winter temperatures, possibly explaining the difference between the two sites.

a)
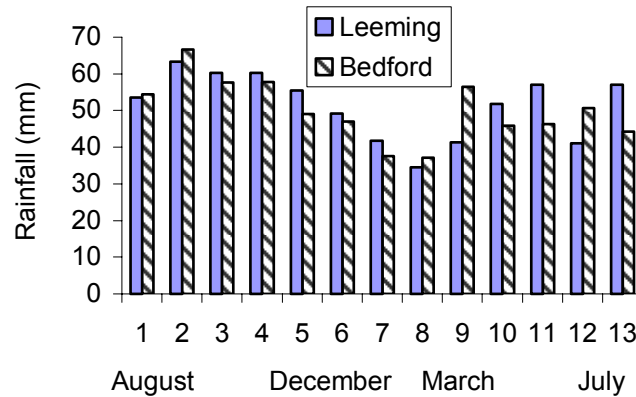
b)
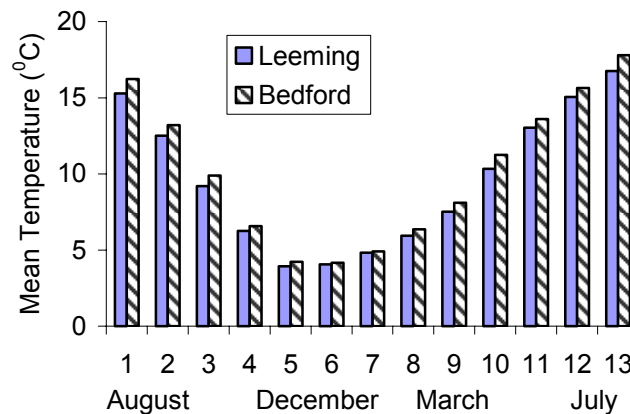
Fig. 5 Comparison of the weather data from Leeming and Bedford a) total rainfall and b) mean temperature over a yearly set of thirteen 4-week periods starting from 1 August.

Effects of weed control

The most critical issue for the user is arguably how the weeds and subsequently crop responds to weed control practice. Two examples are given in Tables 4 and 5. Table 4 presents the output of the biological models for the control of common chickweed. In the absence of weed control the weed will reduce yields from 10 t/ha to only 6 t/ha under the conditions at Leeming. If isoproturon is applied in October at a high rate, control will be excellent and yields will approach the weed free yield. If the herbicide is applied at lower rates or later in the year (when the weeds are larger) control is poorer and yield losses are greater. If

florasulam (Boxer) is applied at a high rate it will control the weed but a lower rate will not. Trifluralin will give some control, slightly increasing yields, whilst amidosulfuron (Eagle) has no effect and yield losses are the same as the untreated. These different weed responses are based on the control values in the herbicide data base (section 1.6) which are used to calculate the reduction in the weed green area and thus the yield loss the weeds can cause (see above).

The models have also been modified to accommodate the presence of herbicide resistant biotypes of some weeds. Table 5 gives an example for the most abundant species exhibiting resistance, black-grass. Clodinafop + trifluralin (Hawk) and iodosulfuron + mesosulfuron (Atlantis) will give high control of black-grass and thus yields approach the 10t/ha weed free yields. Isoproturon is less effective on the weed and thus yields are lower. If the black-grass has target site resistance the clodinafop treatment will also fail, but this type of resistance will not affect the other two products. If the weed has the ability to metabolise the herbicides the clodinafop and the isoproturon will be less active and so yields decline. The most robust treatment is the iodosulfron + mesosulfuron mixture, as this protected yields from competition from all three types of black-grass. However, it should be pointed out that although little resistance exists currently to Atlantis, careless use could result in increased resistance. The herbicide resistance sub-model will emphasise inappropriate product use that increases this risk of resistance.

Table 4 Response of crop yields to the use of several treatments to control common chickweed at 205 plants/m^2 (products and dates of treatment) (*Leeming site, ploughed, crop sown 1 October, weed free yield 10t/ha*).

Herbicide treatment	Dose (kg or l/ha)	Date of application	Wheat yields (t/ha)
None	N/a	N/a	6.0
Quantum	0.02 kg/ha	23-Mar	9.4
Alpha Isoproturon	5.0 l/ha	23-Oct	9.4
	3.0 l/ha	23-Oct	6.0
	5.0 l/ha	23-Nov	7.4
Boxer	0.1 kg/ha	23-Mar	9.4
	0.05 kg/ha	23-Mar	6.0
Alpha trifluralin	2.3 l/ha	05-Oct	7.3
Eagle	0.04 kg/ha	23-Mar	6.0

Table 5 Response of crop yields to the use of several treatments to control susceptible, target site and metabolic resistant black-grass at 275 plants/m^2. (*Leeming site, ploughed, crop sown 1 October, weed free yield 10t/ha, herbicides all applied 23 December*).

Herbicide treatment	Dose (kg or l/ha)	Resistance status of black-grass		
		Susceptible	Target Site Resistant	Metabolic Resistant
None		5.6		
Alpha Isoproturon	5/l/ha	6.8	6.8	6.4
Hawk	2.5l/ha	9.2	6.1	7.7
Atlantis	0.4 kg/ha	9.4	9.1	9.1

Thus, the biological models will accommodate a series of different scenarios, ranging from different cultivations, through effects of drilling dates and sites, to the effects of pre- and post-emergence herbicides.

1.4.2 The biological model of weed dynamics in a crop rotation

One of the main aims of Weed Manager was to provide information and advice on strategic management of weed populations over several years in a crop rotation. Unlike most other plant protection decisions, the consequences of weed management can persist for many seasons. 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 Appendix D.

The model is based on the life cycle model developed by Moss (1990) for black-grass (*Alopecurus myosuroides* Huds), 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 black-grass and wild oats (*Avena fatua* L.) respectively. Because of the large uncertainties present in the weed life cycle, it is necessary to describe the population changes by probability distributions, leading to a *stochastic* model. However, using probabilities for every step is likely to make the model 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/m^2) immediately after harvest in two layers: the shallow layer, 0–50 mm, and the deep layer, 50–250 mm. The shallow layer contains the seeds that might germinate; the deep layer is the rest of the plough depth, so contains seeds that may be brought up to the shallow layer by cultivations.

A series of processes determines the seedbank 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 operations cause much lower proportions of the seeds to be exchanged. A proportion of the seeds in the shallow layer germinate to produce immature plants. Cultivations or herbicides kill some of these, those remaining develop into mature plants. 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 die during the year.

Some of the processes outlined above depend on the weed species, some on the operations applied and some on both. The effect of cultivations on the exchange of seeds between the layers is independent of the weed species and the timing, because it depends only on the physical operations. Other than the parameters quantifying these exchanges, all of the others are stored in databases so that they can be revised independently of the model.

The germination rate depends on the species: very low in poppy, for example, and almost all of the seeds in volunteer oilseed rape and field beans. Similarly the mortality rate varies widely, up to the extreme case of barren brome, which does not survive between seasons in the deep layer. In contrast poppy seeds are highly persistent. Similarly, the number of seeds produced and their viability are species dependent.

The most complex interactions are those that kill the immature plants. The effect of cultivations depends on the drilling date and the seasonality of emergence of the weed. The model uses early, mid and late sowing dates for autumn and spring crops to determine when operations are performed. It is assumed that operations performed around the time of drilling will kill any emerged seedlings, so the timing of emergence determines the number of weeds that survive. The method used for cohort emergence in the within-season model is used to predict the proportion of plants emerging from harvest until 60 days after sowing. The kill rate due to cultivations is then the proportion that emerged before sowing. In general, this will be higher for later sown crops. As the aim of the rotational model is strategic, there is no attempt to model individual herbicides. Instead four cost bands, which depend on the crops, are used. The kill rate at a given cost is lower for a weed and crop combination that makes the weed difficult to control (e.g. herbicide-resistant black-grass in a winter cereal) than for one that is easier to control. For some weed species increasing herbicide cost will not increase control.

In order to provide a clear display to the user, and 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 bands used to set the initial weed density for the within-season model, but the full range is divided into 6 bands (instead of 4 input bands) to give greater resolution. The effects of cultivation methods on the seedbank are substantial and systematic. Therefore, the bands for the shallow layer are derived from the weed density bands in such a way that the top five seedbank bands generate weed populations, covering the full range when ploughing is used in the absence of herbicides. The lowest band is set to correspond to the lowest weed density band when using non-inversion cultivation. This ensures that the behaviour of the first year of the rotational model is consistent with the within-season model. Other than the cultivation method, the most important parameter linking the two sets of bands is the germination rate: if it is high then the number of seeds required to produce a given weed density is low.

The deep layer bands are derived from the shallow ones, by calculating the ratio between them that would exist if the model were in steady state. Although this is rarely the case in practice, it gives a reasonable estimate for well-controlled weeds. The ratio depends on the parameters for seed movement between the layers and on the seed mortality rate.

When the model is initialised from the within-season model, the plant density numbers corresponding to the ends of the band chosen by the user are converted by the same method to give an initial range of seed populations in each layer. It is assumed that the actual number in each layer is a random number uniformly distributed over this range. The model described above is applied to the four states corresponding to all the combinations of the upper and lower bounds for the two layers. The lowest and highest values resulting for each layer are taken, and the seed populations are assumed to be uniformly distributed across this range. The required state variables, the probabilities of being in each band, are then the proportions of the total range lying within each band. For the purposes of the interactive display, the state is then assumed to be the band with the highest probability. However, the decision model uses these probabilities and uses them as the initial state for the following year, resulting in a stochastic model.

Examples of the results of the model will be discussed together with those from the decision model below.

1.5 Decision models

1.5.1 The decision model for management of weeds within a season

The within-season decision model is used when the user selects the *suggest treatments* action 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, based on the previous season's harvest date and a fixed sowing date. The margin used is the value of the grain less the herbicide and cultivation costs. The suggested treatment list is produced within a reasonable time on a typical office PC. The decision model is described in more detail in Appendix F.

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 green leaf area (GAI) of the weeds and wheat at the time of canopy closure. As described above, the timing of weed emergence is determined by the previous harvest date, the sowing date, and the tillage operations between these dates. The other cultivation operations, such as rolling or tine weeding, operate in the model in the same way as herbicides and are treated as such by the decision model. The emergence timings then determine the growth of the untreated crop and weeds to canopy closure. This date is unaffected by any herbicide treatments applied during the season. Within the model, the effect of herbicides is simulated by reducing the GAIs of the weeds at the predetermined canopy closure date, and calculating the effect on crop yield based on these GAIs. This separation of the effects of cultivations and herbicides 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 operates 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. If no cultivations have taken place primary and secondary cultivations can be selected. These selections can be made provided at least 2 days remain before drilling, all the feasible programmes of 1 or 2 cultivations are considered, in which the first takes place on the day after the decision day and the second, if there is one, 1 day before drilling. These timings allow the first (primary) cultivation to stimulate the emergence of weeds that can be killed by the second. Feasible combinations are those that will result in a suitable seedbed. The sequence giving the best margin is retained. In addition to this, 2 further fixed programmes are used: plough, harrow

and drill on 3 consecutive days, and direct drilling. If a cultivation has already taken place, the search is limited to considering a second cultivation. If there have been no cultivations, but the date is within 2 days of drilling, the only option is direct drill.

Having chosen up to 3 cultivation sequences, the second phase is to select the herbicides to be considered. The user will have specified a working list of herbicides, but post-drilling cultivations (eg. tine weeding) are also considered. Some herbicides can be applied at different doses, but there are several rules that restrict when they can be applied. The most important rules are the product approvals, which are mandatory and cover dose and timing. There are also recommendations from the herbicide manufacturers that cover circumstances in which efficacy may be reduced, such as cold weather and particular growth stages. As the decision model is trying to achieve good weed control, it only considers programmes that meet the recommendations. Finally, product mixtures are restricted to include only those on the system's recommended list. Note that some mixtures, where there are known synergistic effects, are treated as products in their own right. The decision model defines 4 consecutive spraying periods: pre-emergence, autumn, spring and desiccant (pre-harvest). 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.

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 2 products are evaluated in the same way. Any product or mixture that has efficacy equal to or lower than 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.

In the final phase, the list of programmes is filtered to remove poor solutions and repetitions of very similar programmes. Firstly, all solutions giving a margin less than 90% of the best are removed. After this, a filter is applied to each group of solutions with the same cultivations that searches for programmes containing identical herbicides at different doses or times, and leaves only the best *n* of them. Initially *n* is set to the give the desired number of solutions in the list, which normally results in more solutions than required, because there are

several herbicides. It is then reduced progressively until the desired list length has been reached. The normal target is 20 when the lists for all the cultivation options are combined.

1.5.2 The decision model for management of weeds in a rotation

The rotation 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. Full details are given in Appendix E.

As described above, the biological model is a stochastic simulation of seedbank dynamics using two soil layers, 0–50 mm and 50–250 mm, to describe the seedbank. Within each layer, the seedbank is divided into 6 bands, so the state variable for a single weed is a pair of integers (i, j), each lying between 1 and 6, 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 4 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.

This formulation of the model allows it to be optimised using a finite horizon, stochastic dynamic programme (Howard, 1960). Stochastic dynamic programming is designed to solve sequential decision problems of this type. The solution takes the form of the policy that maximises the long-term expected (mean) return. A *policy* defines the decision to take for every possible state of the system. If the model is stationary (the available states, decisions and transition probabilities are identical each year) and obeys the axioms of a Markov process, it is possible to obtain an infinite horizon, by iterating for many years until a steady-state is reached. The finite horizon solution used in Weed Manager maximises the expected return over a period of 8–10 years depending on the length of the rotation. It could be converted into an infinite horizon problem by using a hierarchical approach (Kristensen, 2000), in which a complete rotation was one iteration of the larger problem, but the solution time would be prohibitive.

The solution time also places a limit on the number of weeds that can be optimised simultaneously. Each weed has 36 possible states (6 for each layer), and the solution time is proportional to 36^{2n}, where n is the number of weed species ($36^2 = 1296$). This is illustrated by a test on a 2.8 GHz PC, in which the solution for 2 weeds required about 15 s, and for 3

weeds required 15540 s (over 4 hours). As a result, Weed Manager simply considers the two most competitive weeds in the optimisation.

In Weed Manager, 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 rotation is the sum of the returns for the years, weighted by a discount factor to account for interest and inflation, plus 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 were maintained in steady-state, weighted by the discount factor (Sells, 1995).

Tables 6-9, which are taken directly from the program output, illustrate the results. A base case was set up as shown in Table 6, using a rotation of 2 years of wheat followed by a winter break crop, with a mixture of cultivations, moderate herbicide costs and mid sowing dates. The weeds considered were black-grass with target site resistance and barren brome. The initial plant densities were set to the second band, which would equate to low-moderate seedbanks. Note that the table shows the results at the end of the first season, when the seedbanks had increased. The expected margin was £152/ha with a range of £0–303, and the weed seedbank was higher at the end than the start. Table 7 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.

A slight change was made to the base case in Table 8: the break crop in year 3 was changed to spring oilseed rape. This naturally 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 9 shows the result of optimisation. The changes were similar to those in the base case, except for the change to non-inversion cultivation in the year after the break crop. The expected margin was £241/ha, which was slightly less than using winter

oilseed rape. 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, as would be expected. The most significant difference was the improvement in the control of the black-grass population.

The current version of the model tends to favour late sowing as the resultant reduction in weed competition is greater than the yield loss resulting from the late sowing. In reality, late drilling is often not a practical option for reasons of whole farm management. But it does emphasis that there are benefits from late sowing fields with aggressive weed populations.

Table 6 Rotational model example, 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						
black-grass (target resistance)	high	very high	high	very high	very high	very high
brome: barren	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)						

Table 7 Rotational model example, 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						
black-grass (target resistance)	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)	259	307	194	320	322	72
Average margin over rotation £246/ha (209-283)						

Table 8 Rotational 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						
black-grass (target resistance)	high	very high	low	very high	very high	high
brome: barren	high	very high	very low	very low	low-moderate	low
Margin (£/ha)	259	140	86	199	222	43
Average margin over rotation £158/ha (35-281)						

Table 9 Rotational 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						
black-grass (target resistance)	high	low-moderate	low	low-moderate	low	low
brome: barren	high	low-moderate	very low	very low	very low	very low
Margin (£/ha)	259	307	134	337	331	77
Average margin over rotation £241/ha (211-270)						

1.6 Herbicide data collation and storage

The data related to weed control were gathered and collated by SAC. The data were initially sourced from the participating agrochemical companies: BASF, Bayer CropScience (initially Aventis), Dow Agrochemicals, DuPont (UK) Ltd and Syngenta.

In order to ensure that there were examples of active ingredients not produced by those companies, agreement was obtained from Agrichem Ltd, Headland Agrochemicals Ltd, Makhteshim-Agan (UK) Ltd and Monsanto (UK) Ltd to include certain of their products. In most of these cases, SAC entered the data sets because the companies did not have the staff to undertake such work. SAC also entered data for the key participating companies where required and as requested.

The relevant company audited any data entered by SAC, except where there was an agreement that SAC would audit. A different staff member did this from the person who had done the initial data entry where possible, and was only undertaken for the secondary group of companies: Agrichem, Headland and Makhteshim Agan.

Data on physical and cultural weed control was entered by SAC utilising key literature (notably Davies & Welsh, 2001), and available expertise.

The herbicide data that should be included in the system was agreed during the WMSS project Group Leaders and Herbicide Group meetings. The WMSS Herbicide Group including representative of each of the key funding companies, the UKASTA and AICC representatives of the WMSS Steering Group and members of the WMSS Group Leaders as required. The Herbicide Group not only discussed herbicide data management, but also assisted in responding and advising in system design and in selection of herbicide information for the encyclopaedic modules.

Herbicide data collected - Herbicide X Weed Interactions

Spreadsheets were produced to allow the companies and SAC to enter data (example spreadsheets in Appendix I). The spreadsheets have 256 weed species divided into priority species, key species, other economically important species and other weeds/field major flora. The latter group including many species of biodiversity and rarity value to allow the system to extend to such attributes if required. The weeds with known herbicide resistance problems were divided into resistant types, which were included as separate species (black-grass, wild-oats, Italian rye-grass, chickweed, poppy). The activity of each herbicide at each

recommended dose against each growth stage of each weed was entered on a scale S (>90% control; 95% for black-grass), MS (75-90%), MR (50-75%), R (<50%) and U unknown.

It was agreed the basic selection programme would be based on label dose recommendations (level 1) but that extra information on weeds with those doses would be provided where possible (level 2). Again when available, some companies donated data on lower than recommended rates (level 3) – but this was only included as encyclopaedic data rather than part of the selection programme, because of liability concerns.

Other published data on low doses was entered by SAC onto the encyclopaedic section, as was information on a screening programme of rarer weeds undertaken by ADAS Boxworth and SAC Edinburgh (level 4) (see Appendix A).

To obtain mixtures of herbicides, key mixtures were entered as if single products but the system was designed to be able to mix products using an additive control approach. The companies provided information on recommended mixtures and mixtures to be avoided for various reasons, and further spreadsheets were provided for such data entry.

The need for sequences to be part of the herbicide selection programme entailed the development of a further spreadsheet that indicated the time interval allowed between use of individual herbicide products. To this was added a further spreadsheet which included following crop and cultivation requirements after using specific herbicides or mixtures/sequences of herbicides. This information was to be included in the encyclopaedia.

Further information on herbicides collected for the encyclopaedic section included statutory information via LIAISON, a pesticide database programme based at CSL York, and Environmental Information Sheets from the agrochemical companies. Further label information was included, along with lists of weeds and levels of control derived from the spreadsheets described above.

Problems and Solutions

There was considerable discussion regarding allowing reduced dose (below label recommendations) information in the selection process, desired by User Groups. However, the liability problems associated were considered to be too great. Data collection from non-participant companies presented a number of difficulties, which took time and discussion to overcome.

Frequent changes in product approvals and recommendations show the need for regular updating of the database, although once a year, probably in early summer, is probably an acceptable compromise. The basic information/data was collected as required by the Milestones, but updating, detail checking and auditing continued throughout and up to the end of the project.

The lack of information on minor weed species and species with biodiversity and rarity value became very evident as the data was collated. A herbicide screen of less common/rarer weed species of biodiversity value was undertaken at ADAS Boxworth and SAC Edinburgh (Section 1.7 and Appendix A). The principle herbicide active ingredients were included in the screen at half recommended and double recommended doses. The work was split between sites because of the large number of treatments involved. However, again due to liability considerations, the data from these screens was included as advisory information in the encyclopaedic section rather than imbedded within the decision process.

This lack of information on most of the more unusual and rarer species, will hinder the use of the system as a tool for species conservation and management. This would require extensive further screening work to provide a comprehensive database. Nevertheless, a reasonably substantial database has been developed for the Weed Manager encyclopaedia, which will assist users in making treatment selections to assist in species conservation.

1.6.1 Herbicide data import

The herbicide data provided by the chemical companies has to be added to the database so that it is available for use in the encyclopaedia and decision support module. These data have to be updated once or twice a year so dialog applications were written to perform the major tasks required:

- import herbicide sensitivity
- import tank mix data
- import product sequence data
- validate herbicide data

These programs are used by a person responsible for updating the system prior to release of the system. Therefore, in this section the term 'user' does not refer to the farmer/adviser using Weed Manager.

The label data provided by the companies was in a format that could be directly imported into a table in the database.

1.6.2 Herbicide sensitivity data

The data were supplied on predefined spreadsheets (Section 1.6 & Appendix I). The header of the spreadsheets contained some basic information about the product so that the data could be linked to the correct statutory product information held in the DSE pesticide database. The header also contains the HRAC groups for the product, which are used in assessing the risk of developing herbicide resistance. The rest of the data on the spreadsheet defined the sensitivity of each weed to the product at each stage.

The herbicide sensitivity importer is a dialog-based program (more detail can be found in Appendix G). The importing of the data is carried out in a worker thread. The program is designed for level 1, 2 (company data) and 4 (glass house trials) data (see section 1.6). In order to check that there are no inconsistencies in the data a herbicide data validation program has been written.

The spreadsheets could contain actual products or generic names. The generic names are converted into actual products, which have the same composition. This is necessary because the module takes the cost of products into account when calculating the efficacy of the treatment.

1.7 Herbicide screening trials

Objective

To investigate the herbicide tolerance of rare and beneficial weed species native to Britain, where no data were available.

Due to the glasshouse space logistics, the herbicide screen was split over two sites, ADAS Boxworth and SAC Edinburgh (2001-2002). Half of the herbicides were screened at each site against the full list of weeds at both sites. Standards were included to monitor scientific continuity between the two sites. A total of 20 weed species were tested against 20 herbicides. The details of the methodology can be found in Appendix A. These data are displayed in the herbicide encyclopaedia under the additional information section (level 4) and are not used in any decision making processes, but are useful reference data. They can also be accessed via the weed encyclopaedia for the specific weed species tested.

1.8 Validation

1.8.1 Desk-based validation

As the project reached its later stages the weed agronomists in the project team spent a number of days together exploring the outputs from the models and assessing from their experience whether the results were realistic. As there were many combinations of weeds, cultural practices and herbicide treatments this took some time. As a result of this activity a number of the parameter values in both the within-season and rotational models were reviewed. The assessments also made the experts reconsider some of their perceptions, as the outputs from the system can challenge pre-conceived ideas. The experts consulted with the system designers to record and discuss the problems and make the necessary changes to the models.

1.8.2 Field validation trials

Objective

To test that the growth and competition models in Weed Manager can predict yield loss in winter wheat from observations of green area index (GAI). The following questions needed to be answered:-

1. Given the GAI of each weed species at canopy closure, can the loss in wheat yield at harvest be predicted?

2. Given the GAI of each weed species shortly after seedling establishment, can the GAI at canopy closure of each component weed species be predicted?

3. Given the efficacy of a particular herbicide for a given weed species at a specified growth stage of application, can the change (reduction) in GAI due to the application of the herbicide be predicted?

4. Given a change in GAI of weed species due to a particular herbicide, can its effect on change in crop yield loss due to the weed damage be predicted by assuming that this change in GAI had occurred at time of canopy closure?

A range of weed species at different densities, crop sowing dates, geographic locations and herbicide applications were included (Appendix B). The within-season biological model was tested using data collected in the field trials (Appendix B).

1.9 Weeds and herbicide encyclopaedia

The encyclopaedia had to support three criteria:

1. To make all information used in the rotational and within-season modules of Weed Manager available to the user.

2. To provide a simple interface that would be user friendly and intuitive and incorporated user data requests.

3. To ensure that the design made the encyclopaedias easy to update.

Full details of the structure of the Weed encyclopaedia can be found Appendix C.

System design

If data had to be available both to the Weed Manager modules and to the encyclopaedia then it would have to be held in a database available to both. It was decided that all encyclopaedic information should be held in a central database, which would reduce problems of updating and would provide the simplest way of satisfying the last aim. Parts of this could be accessed both by the Weed Manager system and the encyclopaedias, so that the system information was both current and available. Where information was unlikely to change, 'static' pages could be generated, while the database structure would determine that new static pages would have the same design as older pages. Although local databases could be held at different sites, they would be merged several times a year to create an updated permanent central database.

User needs

Users helped draw up the design brief at the first focus groups held in December 2000. They specified:

For products:

- Basic information on products
- Some information on tank mixes and adjuvants
- Less importance of off label information
- Environmental information

For weeds:

- A single up-to-date source of weed biology
- Basic information on the full range of weeds
- Simple, clear text
- Good quality images and graphics
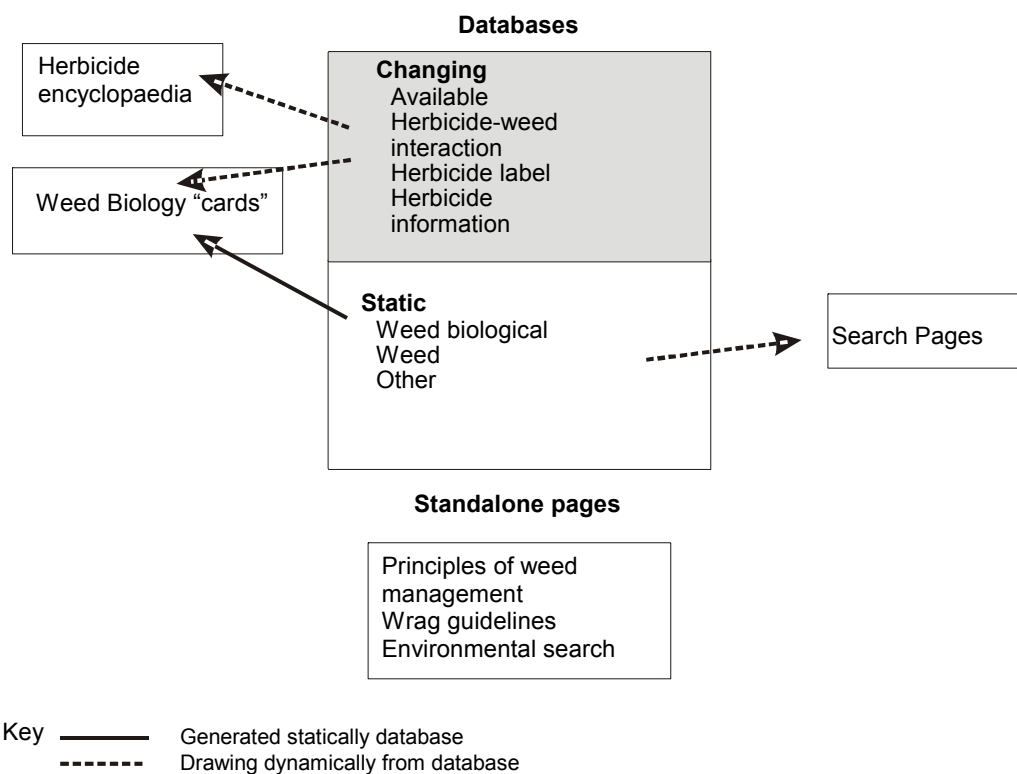- Possible card index format

Additions:

- Weed identification system
- Some information on weed management specifically for herbicide resistance management

The interface design was refined and presented to users in an iterative process during the WMSS project.

Specifications

Encyclopaedic information has been designed for viewing within the ArableDS Browser. This means that the format uses HTML and JavaScript as languages to build and run the pages. The encyclopaedias run like an extended web site, with simple pages whose content is stable and pages drawn from databases. The final specification led to an encyclopaedia in several parts. The relationship of the encyclopaedias and databases are shown in Fig. 6.

Databases

| Herbicide encyclopaedia |
| Weed Biology "cards" |

Changing
Available
Herbicide-weed interaction
Herbicide label
Herbicide information

Static
Weed biological
Weed
Other

| Search Pages |

Standalone pages

Principles of weed management
Wrag guidelines
Environmental search

Key ——— Generated statically database
----- Drawing dynamically from database

Fig. 6 The relationship of the encyclopaedias and databases in Weed Manager

The user needs visual clues to the location of the pages they are using, and therefore product related pages have green livery, while weed related pages have brown livery with card index tabbed tops.   The style of the pages is controlled using external style sheets for ease of future editing.

Herbicide information

The herbicide information is located within a dynamic encyclopaedia with all information drawn from a database at the time of use. The information is divided into appropriate sections (Table 10), which can be accessed at a single button click. All herbicides in the system are therefore accessible from just one page (using an ActiveX control to link with the database).

Table 10 Contents of the herbicide encyclopaedia.

Section in encyclopaedia	Source of information
Product name, active ingredients and formulation	Companies
Company website link	Liason
HRAC group	Companies
Statutory information	Liason
Label information	Companies
Tank mixes and sequences	Liason/Companies
Herbicide effects – used within system	Companies
Herbicide information extra to system	Literature
	WMSS glasshouse experiments
Environmental information	Voluntary Initiative

Weed Information

Information on weed biology is available in index card format so that almost all the information is visible with no need to scroll. Part of each 'card' links dynamically to the herbicide effects database to display the information used to generate Weed Manager model output. Each weed has 8 separate 'cards', displaying information under the following headings: biology, location, controls, environment, description, young plant, mature plant and fruit/seed.

Weed identification system

The weed identification system draws actively from the database, so that more plants can be added easily at future stages. Plants are divided into grasses and broad-leaved weeds with identification as young plants or flowering stage. For grasses a further subdivision shows the leaf ligule.

Principles of weed management

This general guide to weed management was based on information that does not need to be updated frequently and so could be developed as stand alone web style pages. This part of the encyclopaedia includes background information on weed biology, soils, weed control in conventional and organic systems, and access to the WRAG guidelines (Herbicide resistance

management), and biodiversity. There is a guide to growth stages and yield reducing cover (green area) of some common weed species.

Environmental searches

As the development of Weed Manager progressed it was clear that users would require information on how weeds interact with the environment. Weed Manager now contains a search to enable users to find weeds with particular characteristics such as support for farmland birds (a prime environmental indicator), butterflies and rarity. At present this is a stand-alone page, but it can be converted to a database driven page in the future.

Validation of encyclopaedic materials

Before the encyclopaedic information was published each database area was edited and experts, some of whom were not in the project team (Table 11), carried out specific validation. Herbicide Label information was checked by participating companies.

Table 11 Weed Biology encyclopaedia data validation by experts.

Area for validation	Validated by
Weed list for rarity	Amanda Miller (Plantlife) Phil Wilson
Bird food	Richard Bradbury (RSPB)
Weed photographs	Martin Parham (Herbiseed)
Population graphs and information	Peter Lutman (Rothamsted)
Text and other areas	ADAS

1.10 Help system

The Weed Manager help system (Wmhelp) needed to be developed by a 'naïve' system user, who was conversant with farm management, but had not been involved in the development of the system. Therefore, James Marshall-Roberts, a placement student from Harper Adams University, seconded from Syngenta in 2005, developed Wmhelp. Although new to ArableDS he was confident about using and exploring the system.

The Wheat Disease Manager help system (WDMhelp) was used as starting point to the development of Wmhelp. Some topics, such as general farm management issues (e.g. creating and applying pesticides) were similarly treated in WDMhelp, so could be edited for Wmhelp.

For Weed Manager the help author noted specific issues, as he became familiar with the system. Individual help pages were then created covering each topic, taking screen shots as

appropriate. Once the system had been written pages were ordered systematically. Links to similar topics were created to aid navigation.

At the outset of the WMSS project the decision was made to make available to users all information that was used in modelling and calculating system output. This would increase user confidence in the module. Most of this information (herbicide x weed effects and biological parameters) is displayed in the Weed Manager encyclopaedia (Appendix C). However, background information on farm economics, and the mathematical models used are found in the biological models and rotational model crop information Wmhelp pages.
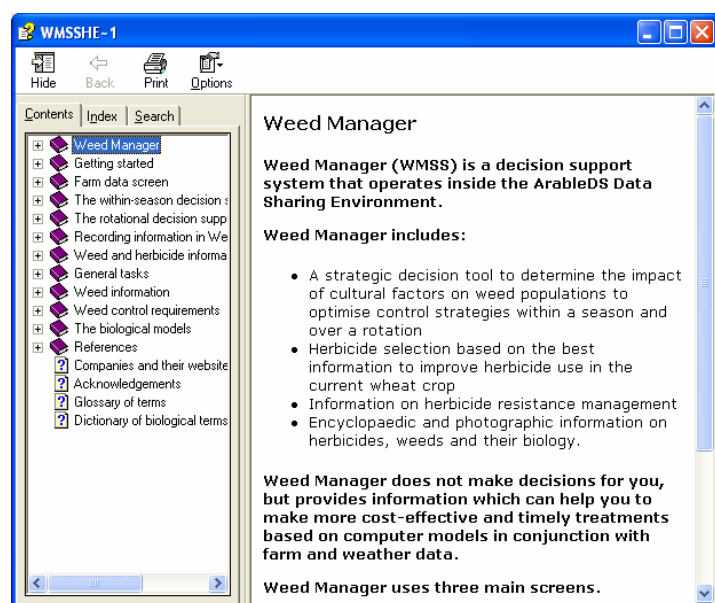

Fig. 7 Front page of the help system.

Wmhelp can be accessed from the within-season or rotational screens of Weed Manager by clicking the [?] icon or from Help on the menu bar. Wmhelp was developed using 'HelpKit HTML Help Authoring Solution' from DevComponents.com.

1.11 Installation

Weed Manager is a module that runs within the ArableDS DSE. The installation program used to install the DSE also installs all the data access software required by the modules. The DSE installation program requires that the modules be installed using a Microsoft windows installer database, that is the installation program must consist of an msi file and a data cab file. The Weed Manager installation has been written using InstallShield X professional edition.

1.11.1 Installation program structure

The files used in the installation are organised into three sections known as features; the encyclopaedia, the module and files that are common to both parts.

The encyclopaedia
The encyclopaedia requires four groups of files, known as components, to be installed.

1. The files that are required by the Rothamsted browser to provide the contents page and search facilities.

2. The file to add the encyclopaedia to the browsers list.

3. The file to provide access to the database containing the data

4. The encyclopaedia pages. These files are not listed individually in the installation program because of the large number of files and possible variability of the structure between versions. Instead the facility, called dynamic file linking, is used to add all the pages from a specified folder.

The module
The module has eighteen components. Most of these components contain just one file so that the installation program complies with 'best practice' requirements of having one executable file in a component. In addition to the components for the executable files, there is a component to install the spray nozzle selector program and its data and a component to install the files used to tell the DSE about the module.

The common files
There are two components in this feature: the database containing all the weed and herbicide data and the icon used to identify the module.

1.11.2 Location of installed files

The files are installed on the users PC relative to the existing ArableDS and browser files; the user does not get asked to specify the destination for the files. The encyclopaedia pages are installed in a 'WMSS' subdirectory of the existing ArableDS/DESSAC/Encyclopaedia directory. The module executable and data files are installed in a 'WMSS' subdirectory of the existing ArableDS/DESSAC directory.

The files used to add the encyclopaedia to the browser and provide the search facilities are installed in subdirectories of the browser installation. The spray nozzle selector is installed in an 'snss' subdirectory of the existing ArableDS/DESSAC directory. The location of the

existing files is carried out using a system search at the beginning of the installation process. The required directory names are then generated using script.

1.11.3 Weed Manager upgrades

The use of dynamic files means that new versions cannot be created using a minor upgrade. A major upgrade must be used and a small patch is created. This patch changes the version number to match that of the new installation program.

1.12 Dissemination

In the first four years of the project various dissemination options were considered. The conclusion was that Weed Manager should be released as part of the ArableDS suite. The major reasons for this were:-

- Non specific updating costs, i.e. weather, pesticide data and general information could be shared
- Support and help were already in place
- The databases, browser and interface existed already
- Farm information could be input to a central store for all modules

Dissemination was broken down into three phases; Activities prior to launch; launch; and post launch advertising, training, help and support.

Advertising through the years prior to product launch was restricted to limited software demonstration at venues such as HGCA Roadshows, and the Cereals events. Feedback from these events was incorporated into software design where possible. Weed Manager was promoted in various popular press articles (Farmers Weekly, Crops, Crop Protection Magazine) and included in a number of presentations and posters at scientific conferences over the 5 years. Demonstrations of the system took place at ArableDS events, such as ArableDS2005 training sessions and the ADAS Open Days (Appendix J).

Weed Manager was demonstrated at Cereals in June 2005 and posters, information, handouts and in house magazine articles shown at collaborating company roadshows and events. Half page articles were published in Farmers' weekly, Crops and LINK magazine.

Weed Manager was officially launched on 18th July 2005 with two training workshops held on 12th and 19th July at ADAS Boxworth. The Weed Manager website was re-launched with

details of how to purchase a copy of Weed Manager (contact WeedManager@adas.co.uk) along with a help line for enquiries.
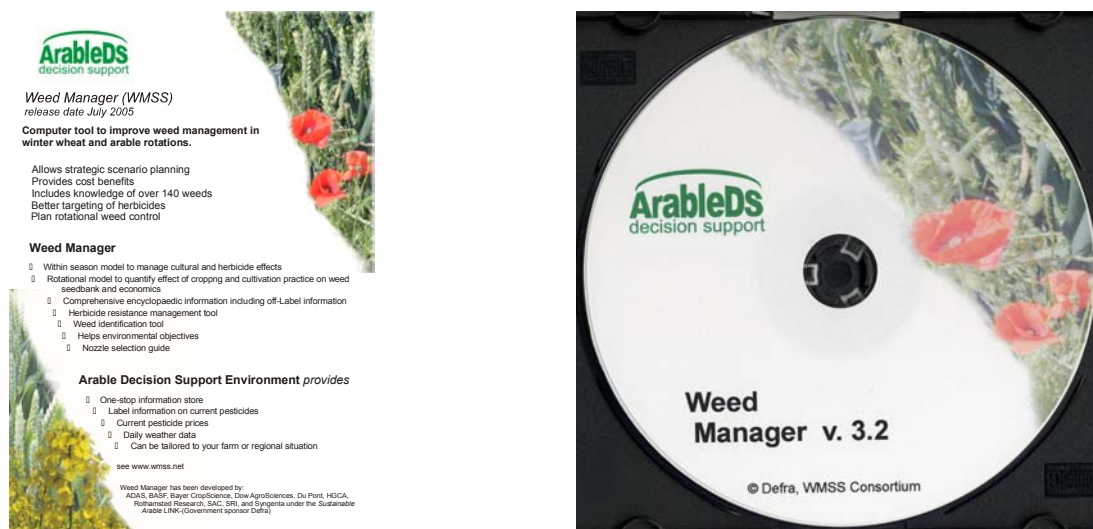
Fig. 8 Weed Manager Handout left and CD right

The Weed Manager help line was manned during office hours from 18th July 2005 onwards. A triage system was put in place. An additional workshop was held in Edinburgh at SAC on 26th September 2005 for users in the northern region.

Problems associated with Weed Manager were usually due to user error and could be rectified at the help desk.

By the end of September 2005 there were more than 50 users of Weed Manager, including Farmers, advisors, academics and other industry users.

1.13 The future of Weed Manager

As the current version of Weed Manager is for winter wheat only the obvious progression of the system would be to develop it into other cereals and broad-leaved crops (oilseed rape or beans in particular). As the project has evolved the interest and importance for improved arable biodiversity has increased. Weed Manager can already be used to understand the impacts of retaining levels of beneficial weed species against crop yield, so would potentially be a useful tool to link in with new agri-environment schemes, but would need to be enhanced for this purpose. Understanding the impacts of rotational weed management have proved to be a popular feature of the current system and could be extended to make the system more robust across a crop rotation. There has been some interest from the organic sector in Weed Manager, as the herbicide element can be ignored and the impacts of cultivations and other

agronomic factors used. To enhance its appeal to an organic grower more crops would need to be added to the rotation (including horticultural crops) and the use of mechanical weeding included as a cultural option.

2.0 ACKNOWLEDGEMENTS

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4.0 GLOSSARY OF TERMS

Term/Abbreviation	Description
ADO	ActiveX® Data Objects
DESSAC	Decision Support System for Arable Crops
DSE	Data sharing environment
DSS	Decision support system
DLL	Dynamic Link Library
GAI	Green area index
HRAC	Herbicide Resistance Action Committee
MFC (view)	Microsoft ® Foundation Class Library
OCX	OLE Custom Control or ActiveX control
OLE	Object-orientated technology that enables development of reusable software components
WMSS	Weed Management Support System
WRAG	Weed Resistance Action Group

5.0 ICONS

Weed Manager uses icons to present information both in the system and encyclopaedias

Cultivation icons used in the within-season module

Harvest

Sowing date

Harrow

Plough

Tine

Rollers, power harrows and heavy tines

Tine weeding, inter row hoeing

Disc, heavy disc

Herbicide icons used in the encyclopaedia

LERAPS

Harmful to bees

Very poisonous

Flammable

Harmful

Irritant

Corrosive

Flammable

Harmful to the environment

Harmful to fish

Weed icons used in the within-season module and encyclopaedia

Resistance risk

Highly competitive

Winter persistence

Supports BAP species bees

Supports other insects

Supports butterflies

Supports birds

Rare plant

Project Report No. 388
(Appendices A - K Pgs 49 - 127)

February 2006

Development and validation of 'Weed Management Support System' (Weed Manager)

by

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6.0 APPENDICES

*Appendix L is available electronically on the HGCA website, and does not form part of the printed report.

Herbicide Screening experiments

Materials and Methods
Trial design, planting and maintenance
The herbicide screen was blocked by herbicide, and there were three replicate blocks. Ten seeds of each weed species (Table 1) were sown into individual 3' plastic plant pots containing John Innes No. 2 (low OM sterilised soil) and pots were thinned to 3 plants per pot when seedling emerged. Pots were maintained in the glasshouse under the conditions of 18°C day temperature with 12 hours daylight and 10°C at night. The benches were covered with capillary matting to allow watering from below, and initially the pots were covered with clear plastic to prevent the seedlings drying out.

Table 1 The list of weed species tested in the glasshouse herbicide screening experiments.

BAYER code	Latin name	Common name
SCAPV	*Scandix pecten-veneris*	Shepherd's-needle
ANTAR	*Anthemis arvensis*	Corn chamomile
ANTCO	*Anthemis cotula*	Stinking chamomile
BRSNI	*Brassica nigra*	Black mustard
CENCY	*Centaurea cyanus*	Cornflower
CENNI	*Centaura nigra*	Knapweed
CERVU	*Cerastium vulgatum*	Common mouse-ear
CHYLE	*Leucanthemum vulgare*	Oxeye daisy
DAUCA	*Dauca carota*	Wild carrot
ECHVU	*Echium vulgare*	Viper's-bugloss
GAESE	*Galeopsis speciosa*	Large flowered hempnettle
GASPA	*Galinsoga parviflora*	Gallant soldier
LYCAR	*Anchusa arvensis*	Bugloss
MATCH	*Matricaria recutita*	Scented mayweed
MELAL	*Silene latifolia*	White campion
PAPDU	*Papaver dubium*	Long-headed poppy
PAPHY	*Papaver hybridum*	Rough poppy
RANAR	*Rananculus arvensis*	Corn buttercup
RESLU	*Reseda lutea*	Wild mignonette
SSYOF	*Sisymbrium officinale*	Hedge mustard
STEME*	*Stellaria media*	Common chickweed
POANN*	Poa annua	Annual meadow grass

* *standard weed species used at both sites*

Herbicide applications
For the post-emergence herbicides the plants were sprayed when they had reached approximately the 3-leaf stage, which required grouping the species into 3 different spray batches based on their growth stage. The 3 replicates were sprayed in a covered polytunnel using a knapsack sprayer, fitted with a 1m wide boom with flat fan nozzles, at a spray pressure of 2-3 bar, applied at a rate of 200 l water /ha. The products were applied at two rates of the chemical, normal field rate and half field rate (Table 2).

Table 2 Herbicide treatments and application rates for glasshouse screening experiments.

Herbicide product	Active ingredient	Application rates	
		Full field rate	Half rate
Eagle	Amidosulfuron	40.0 g/ha	20.0 g/ha
Harmony -M	Thifensulfuron	60.0 g/ha	30.0 g/ha
Lexus	Flufensulfuron	15.0 g/ha	7.5 g/ha
BASF MCPA	MCPA	3.0 l/ha	1.5 l/ha
Duplosan	Mecoprop-P	2.0 l/ha	1.0 l/ha
Quantum	Tribenuron	20.0 g/ha	10.0 g/ha
Boxer	Flurasulam	0.15 l/ha	0.075 l/ha
Picopro	Picolinofen + PDM	2.0 l/ha	1.0 l/ha
Oxytril	Bromoxynil/Ioxynil	1.5 l/ha	0.75 l/ha
Lotus	Cinodon-ethyl	0.25 l/ha	0.125 l/ha
Starane 2	Fluroxypyr	1.0 l/ha	0.5 l/ha
Dow Shield	Clopyralid	1.0 l/ha	0.5 l/ha
Arelon	Isoproturon	4.2 l/ha	2.1 l/ha
Panther	DFF + IPU	2.0 l/ha	1.0 l/ha
Crystal	Flufenacet + PDM	2.0 l/ha	1.0 l/ha
Fortrol	Cyanazine	2.5 l/ha	1.25 l/ha
Treflan	Trifluralin	2.3 l/ha	1.15 l/ha
Avadex Excel 15G	Tri-allate	15.0 kg/ha	7.5 kg/ha
Ally*	Metsulfuron	30.0 g/ha	15.0 g/ha
Stomp*	Pendimethalin	1.5 kg/ha	0.75 kg/ha

standard herbicides used at both sites

Assessments
Post-spraying the pots were returned to the glasshouse and assessed 1-2, 5-7, 14-16 and 21-24 days after treatment for any herbicidal effect. Assessments were on a visual % damage basis, using the 0-9 scale

Results
The results from the herbicide screening experiments are displayed within the system on the relevant herbicide or weed page, called additional information. These data are for reference only and are not included in any decision making processes.

Field validation trials
Materials and Methods
In the autumn of 2002 field trials were established (Table 1) in a crop of winter wheat at two different ADAS sites, Boxworth (Cambridgeshire) and Rosemaund (Herefordshire) and at SAC in Edinburgh. In 2003 two trials were established at ADAS Boxworth only (Table 1). Fields were selected with a low natural weed population and the desired weed species were hand sown.

Table 1. The location and weed species chosen for each field trial site.

Species/trial year	Sites		
	ADAS Boxworth	SAC	ADAS Rosemaund
Black-grass 2002/03	✔ ✔		
Black-grass 2003/04	✔ *		
Chickweed 2002/03	✔	✔	
Cleavers 2002/03		✔	✔ ✔
Cleavers 2003/04	✔		

✔ ✔ *represents two drilling dates for that particular experiment.*
individual plots were selected from a large black-grass trial, with a natural population of black-grass, therefore no specific trial was sown for this project in 2003/04.

Where two drilling dates were required the target drilling dates were late September and late November. No herbicide treatments were applied other than the trial treatments, but all other farm inputs were to standard commercial practice for that particular farm.

Trial design
For the trials with multiple drilling date a split plot design was used, with 3 main blocks for the 3 replicates, sub-divided into 2 blocks in each main blocks for the drilling dates and sub-plots for the combinations of herbicide programme and weed density. Trials with a single drilling date were a randomised block design. The minimum plot size was 3m x 12m.

Weed density
The densities for each species (Table 2) were selected to cover a range where the models predict that the rate of change of crop yield with weed density is at its highest. Weed seed was hand sown into each plot on the day of drilling ahead of a commercial crop of winter wheat being sown. Weed seeds were purchased from Herbiseed, UK and were known to be from non-resistant populations.

Table 2 The weed species target densities for the field validation trials

	Density (plants per m^2)		
Weed species	Low	Medium	High
Black-grass	6	36	216
Chickweed	6	36	216
Cleavers	4	16	64

Herbicide treatments
Application timings of the herbicide treatments were determined by the growth stage of the weed species. The early herbicide treatment was applied at 2-leaf growth stage of the crop, and the late treatment at the 8-leaf stage and after canopy closure. The choice of herbicide products and doses were weed dependent and are presented in Table 3. Herbicides were applied using a knapsack sprayer and 3m boom, with Lurmark 02 F110 nozzles, at a rate of 200L water/ha and a pressure of 3.0 bar.

Table 3 The herbicide treatments, application timings and dose rates.

Weed species	Treatment Timing	*Application Timing*	Herbicide	Rate	
Chickweed	Early	Post-em (autumn)	Treflan	2.0 l/ha	
	Late	GS30 *(after 1st Feb)*	Ally *(+ Starane)**	7.5g/ha	*(0.5 l/ha)**
	Full control	Autumn	Panther	2.0 l/ha	
		(Ally-Spring, after 1st Feb)	*(fb. Ally if needed)*	*(30g/ha)*	
Black-grass	Early	Autumn (up to 2-3 tillers)	Lexus 50DF	20 g/ha	
	Late	Feb/March	Topik	0.16 l/ha	
	Full control	Autumn post-em	Crystal	4.0 l/ha	
		Autumn 2-3 lvs.	Hawk + Lexus 50DF	2.5 l/ha + 20g/ha	
Cleavers	Early	Autumn	IPU	3.0 l/ha	
		Feb/March	Eagle	20 g/ha	
	Late	Autumn	IPU	3.0 l/ha	
		Crop GS 31-32	Starane *(+Ally if needed)*	0.5 l/ha	
	Full control	Autumn	Panther	2.0 l/ha	
		Spring	Starane	1.0 l/ha	

Assessments

Within each plot one 0.5 m^2 permanent quadrat was marked out for seedling emergence (of crop and weeds) counts. Up to 4 other 0.5 m^2 quadrats per plot were destructively sampled as detailed below:-

i) Seedling Emergence Counts

On one of the weed density plots in each replicate, the number of weed and wheat seedlings was counted every 3 or 4 days, depending on the change in numbers observed, until emergence was complete. When emergence is complete, the numbers of seedlings in a sample quadrat in each plot should be recorded to determine the density of weeds.

ii) Biomass assessments and GAI assessments

On the no herbicide application treatments only, a visual assessment of the ground cover was recorded in one 0.5 m^2 permanent quadrat and all plants were hand harvested and separated into the different species. Individual weeds and crops were counted and a growth stage measurement of weed and crop was assessed and recorded by selecting 6 representative plants from each species. For each species (all weeds including natural populations and crop), the leaves and stems were separated and the green area measured. This process was repeated at each of the following timings on the appropriate plots:-

- Three weeks after Early Herbicide Application *(when symptoms of treatment were visible)*
- At Canopy Closure *(defined as when the GAI of all weeds plus crop reaches 0.75)*.
- Three weeks after Late Herbicide Application *(when symptoms of herbicide treatments were visible)*
- June *(before combining the plot)* – all plots.

iii) Final Crop Yield Harvest from combine yield area

The fertile tillers were counted in each plot using each side of a 0.5m rod placed between the crop rows at 5 points per plot. Plots were harvested using a Sampo plot combine and plots length measurements were recorded. Sample of grain were collected and processed for grain moisture content and a thousand grain weight. Plot yields were calculated.

Data analysis

The data collected from measurements were entered into EXCEL spreadsheets and sent to Rothamsted for further collation and analysis. Given the GAI observed at complete seedling

establishment and daily meteorological records, a model of green area expansion was run in Matlab to predict the GAI at canopy closure in the no herbicide control treatments. The model used parameter values from the literature. These simulations were used to predict the weed GAI before herbicide application. The difference between this value and that observed after applications was compared with the expected efficacy of the herbicide. The ratio of weed species GAI to winter wheat GAI at canopy closure was used as inputs to the equations used to relate these ratios to winter wheat yield loss.

Statistical Analysis of Observed Data
The times of weed and crop seedling establishment were estimated by fitting logistic curve to the seedling numbers observed in the permanent quadrats. The yield of the winter wheat at harvest, the biomass of each weed species prior to harvest and the GAI of each sown species at emergence, canopy closure was subjected to an ANOVA in Gentstat. Regressions between visual assessments of cover and GAI were conducted. The differences between observed and predicted winter wheat yield loss and between observed and predicted GAI at emergence and canopy closure, were also subjected to an ANOVA. Additionally, the simulation models were fitted separately to each replicate and the fitted values subjected to an ANOVA.

Results
The results from the field trials were evaluated by the experts and tested against the model outputs.

Comparison of the predicted and observed crop growth stages from the first season (2002-03) showed   good agreement. The model was compared with data from the black-grass trial at ADAS Boxworth on crop and weed green area index (GAI) and the effect of weeds and herbicide treatments on crop yield. Autumn 2002 was very dry, leading to exceptionally low germination of the weeds. The model predicted slightly higher germination rates and consequently higher weed GAI than were observed. The weed densities were so low that the differences between treatments (weed sowing density and herbicide programme) were not significant. The predicted yields were lower than the mean observed yields, but these differences also were not significant. Inspection of the data showed similarly low GAIs for the other weed species, so the testing was not repeated, as it was unlikely to show additional information.

The second season (2003-04) included fewer weed species, but the weather conditions gave rise to high weed populations resulting in significant yield losses. The model was assessed on the basis of yield loss in sprayed and unsprayed plots (using several spray programmes), thus testing the combined effects of all the steps in the model.

Examples of the results are summarised below from the 2003/04 cleaver and black-grass trials.

Cleaver trial 2003/04 ADAS Boxworth

Crop   Wheat
Sown   14 Nov 2003
Previous harvest   31 Aug 2003 (assumed)
Cultivation   Direct drill (assumed)
Density sown   200-300 based on emergence data
Potential yield   10.6 t/ha (see yield table below)

Weed   Cleavers
Sown   14 Nov 2004
Density sown   low = 4 medium = 16   high = 64

Plant Emergence (mean over treatments)

Date	Crop density	Weed density low	Weed density medium	Weed density high
15/12/03	213	2	9	35
22/12/03	269	4	16	71
5/01/04	278	15	50	182
12/01/04	294	21	73	238
19/01/04	299	26	81	265
2/02/04	301	29	87	273
13/02/04	289	30	83	263

Spray programmes (table from protocol; dates from diary)

Treatment Timing	Application Timing	Herbicide	Rate
Early	08/12/03	IPU (6159)	3.0 l/ha
	04/03/05	Eagle (6131)	20g /ha
Late	08/12/03	IPU (6159)	3.0 l/ha
	02/05/04	Starane (7370)	0.5 l/ha
Untreated	Pre-emergence spray only		
Full control	08/12/03	Panther (6128)	2.0 l/ha
	13/04/04	Starane (7370)	1.0 l/ha

All include 05/12/03 – Pre-emergence spray to kill black-grass – Topik and Avadex.

System data:
Topik ID = 8 (with adjuvant), Dose = 1.0; Avadex ID = 7419, Dose = no data – omit
Eagle doses are 0.03 and 0.04 – use 0.03 on the assumption units are kg.
Starane 2 doses are 0.75, 1.0, 2.0 – use 0.75 in place of 0.5

Cleavers trial results – yield t/ha

	Weed density sown			
Sprays	None	Low	Medium	High
Untreated		9.75-10.73 (10.17)	8.67-9.70 (9.10)	7.17-9.60 (8.51)
Early		10.42-10.84 (10.63)	9.19-11.25 (10.29)	10.01-10.63 (10.37)
Late		9.86-10.84 (10.29)	9.86-10.58 (10.32)	9.96-10.84 (10.37)
Full	10.17-11.15 (10.61)			

Model runs
Used Bedford weather (closest available DESSAC site), with gaps filled by Wittering weather site.

Cleavers model results (parameter set 1.02) – yield t/ha

	Weed density sown			
Sprays	None	Low	Medium	High
Untreated	10.54-10.60	8.23-9.00	5.01-6.09	2.04-2.79
Early	10.60	10.34-10.43	9.66-9.99	7.80-8.58
Late	10.54-10.60	8.27-9.00	5.06-6.15	2.08-2.83
Full	10.60	10.54-10.56	10.36-10.44	9.77-10.04

Comments
- The yield losses in the model from uncontrolled cleavers were far higher than observed.
- The control obtained by the late spray programme was far less than observed.
- Therefore, in order for it to have an effect, the second treatment had to be brought forward to March. With this timing, the yield is similar to that from the Early programme. This was thought to be a feature of the model.

The model was tested using the alternative parameter sets that were considered on 8 March:
1.04 – emergence refitted by Jonathan Storkey, rejected because of large changes in many weeds
1.05 – other parameters fitted by Laurence Benjamin using PCA – small changes to most weeds
1.06 – combination of 1.04 and 1.05
Cleavers model results (parameter set 1.04) – yield t/ha

Sprays	Weed density sown			
	None	Low	Medium	High
Untreated	10.60	10.36-10.45	9.74-10.03	7.84-8.61
Early	10.60	10.58-10.59	10.52-10.55	10.28-10.39
Late	10.60	10.37-10.45	9.76-10.04	7.88-8.64
Full	10.60	10.60	10.58-10.59	10.52-10.55

Cleavers model results (parameter set 1.06) – yield t/ha

Sprays	Weed density sown			
	None	Low	Medium	High
Untreated	10.60	10.26-10.38	9.36-8.76	6.91-7.84
Early	10.60	10.44-10.50	10.00-10.20	8.54-9.16
Late	10.60	10.27-10.39	9.38-9.78	6.96-7.88
Full	10.60	10.60	10.56-10.57	10.44-10.50

Parameter set 1.05 gave even lower yields than 1.02.

Comments
- The evidence is insufficient to recommend a change of parameter sets, especially as the results for black-grass (see below) are different. Further investigation of GAI, etc was required before a decision was made whether the fault is with weed development, crop development or competition.

Black-grass trial (ADAS Boxworth 2003/04)

Crop	Wheat
Sown	16 Oct 2003
Previous harvest	31 Aug 2003 (assumed)
Cultivation	Direct drill (assumed)
Density sown	150-250 based on emergence data
Potential yield	9.2 t/ha (see yield table below)

Weed	Black-grass
Sown	Natural population

Density 100-250 based on early emergence

Emergence

Date	Crop density untreated	Crop density sprayed	Weed density untreated
4/02/04	162-286 (239)	144-358 (260)	98-240 (144)
27/04/04	168-244 (202)	216-316 (253)	208-506 (388)
6/07/07	128-182 (155)	180-218 (200)	124-212 (168)

Spray programmes (table from protocol; dates from diary)

Treatment Timing	Application Timing	Herbicide	Rate
Early *(T4 from BG slots trial)*	02/12/03	Lexus 50DF + Stomp [+Fortune] (6141) + (7214)	20 g/ha + 3.3 l/ha [+ 1.0 l/ha]
Late *(T20 from BG slots trial)*	23/01/04	Atlantis [+ BioPower] (7185)	0.4Kg/ha [+ 1.0 l/ha]
Untreated *(T44 from BG slots)*	*Use untreated plots from black-grass slots trial 2004*		
Full control	21/10/03	Crystal (6130)	4.0 l/ha
	18/12/03	Hawk + Lexus [+Fortune] (6134) + (6141)	2.5 l/ha + 20g/ha [+ 1.0 l/ha]

From system
Lexus 50DF dose 0.02
Stomp 400 EC dose 3.3
Atlantis WG no data
Crystal dose 4.0
Hawk no data

Hawk = clodinafop-propargyl + trifluralin 12.383 g/l
clodinafop-propargyl = Topik (250 g/l, ID = 8 (with adj), dose = 1)
trifluralin = Alpha Trifluralin (480 g/l, ID = 6148, dose = 2.3)

Black-grass trial results

Treatment Timing	Yield t/ha
Untreated	2.13-6.47 (4.91)
Early spray	5.38-9.03 (7.12)
Late spray	8.2-9.11(8.73)
Full control	8.59-9.77 (9.21)

Model runs
Used Bedford weather (closest available DESSAC site), with gaps filled by Wittering.

Black-grass model results (parameter set 1.02) – yield t/ha

Treatment Timing	Sensitive	Resistant
Untreated	6.44-8.48	6.44-8.48
Early	8.61-9.14	8.25-9.07
Late	*	*
Full	9.00-9.18*	8.66-9.14*

*Unable to simulate the late programme due to the absence of data for Atlantis.
Full programme used mixture in place of Hawk due to absence of data.

Comments
- The yield losses from untreated or partly controlled black-grass are too low.
- Parameters sets 1.04 and 1.06 increased the mean untreated yield to 9.0. Set 1.05 reduced it to 6.67, which is still high.

If the density is increased to 250-500 (the range for late emergence) the results are

Black-grass model results (parameter set 1.02, high density) – yield t/ha

Treatment Timing	Resistant
Untreated	4.95-7.36
Early	7.52-8.75
Late	*
Full	8.21-8.98

Comments
- These are closer to the trials, but still on the high side for untreated, and required very high densities. The potential yield probably should be increased, given that the maximum with the full treatment is lower than observed, which would then raise all the yields.
- We need to look at the leaf areas, etc., but these results tend to suggest that black-grass should be made more competitive in the model.

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Weed Manager Encyclopaedia

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Abstract

Weed Manager is a decision support system running within the ArableDS data sharing environment to assist farmers and their advisors with weed related issues within a wheat cropping season and over a six year rotation. The weed manager uses databases to deliver data to the Weed Manager mathematical models. These data are also available to users through the encyclopaedia thus increasing their confidence in the system. Most of the other encyclopaedic information is stored in the database and is viewed with a combination of static and dynamic pages, some of which are wholly or partially database driven. User input in the design process has resulted in an intuitive and easily navigated system.

Introduction

Weed manager was developed to aid people working in the agricultural industry with decisions about weed management in a single crop of winter wheat (within-season module) or in an arable rotation (rotational module). The program was developed to run within the ArableDS data-sharing environment to share common information about pesticides, weather and farm data. (Parsons et al,2004,). The previous ArableDS modules have been released with background information in the form of an encyclopaedia.

Parker and Clarke (2001) have argued that users were more confident in the use of decision support systems when fully aware of the information used to predict outcomes. The primary aim of the encyclopaedia was to make information used in the rotational and within season modules available to the user by sharing information across the system.

The data used by Weed Manager and the common data provided to the ArableDS decision support modules change frequently so are held in databases. Background information about weeds and herbicides also needed to be collected and displayed

There are various internet sites that show information on weeds. For example 'The Arable Seed Identification System' (http://www.scri.sari.ac.uk/asis/) and 'The Ecological Flora of the British Isles' (http://www.york.ac.uk/res/ecoflora/cfm/ecofl/index.cfm, and some PC based programmes such as Hypermedia for Plant Protection (INRA) are available, but no electronic encyclopaedia dealing with all weed related issues exists.

The weed manager encyclopaedia was developed to co-locate and display all this information satisfying three criteria:

1. To increase user confidence in Weed Manager.
2. To provide a simple interface that would be user friendly and intuitive and incorporated user requests.
3. Be easy to update.

Methodology

Design criteria and approach

Previous ArableDS module encyclopaedias (in Wheat Disease Manager and Oilseed Rape Pest Manager) have information on both pesticide products and their targets, so the Weed Manager encyclopaedia needed to display information both on herbicide products and on weeds (defined as arable non-crop plants). In order to increase confidence in the system, it was necessary to make information used in the rotational and within-season modules available to the user and to respond to their-requests for particular data and types of data display.

This led to a two direction approach; effective system design exploited the data needs of both the system and encyclopaedia, while user-consultation helped define and refine both information displayed and the user interface.

User input
An iterative user consultation process was carried out (Park, Parker and Ginsberg, 2004). Users requested the following information:

Herbicides
>Basic information on products
>Some information on tank mixes and adjuvants
>Off-label information
>Efficacy information from other sources
>Environmental information

Weeds
>A single, up to date source of weed biology.
>Basic information on the full range of weeds
>Simple, clear text and good quality images and graphics
>Some information on weed management specifically resistance management
>Weed identification system

And the following design structures
>Card index format with the most important information immediately visible

Encyclopaedia Design
As a result of discussion with users, five encyclopaedic sections were defined; herbicide information including herbicide - weed interactions, weed information including weed - herbicide interactions, weed searches, a simple guide to weed management and environmental searches.

Encyclopaedic information in ArableDS is viewed within the Rothamsted Browser which uses Internet Explorer.   Since the encyclopaedia was to be installed on a local drive, encyclopaedic pages were coded using HTML and Javascript.

Weed Manager was developed with information on over 140 common weeds of winter wheat, and more than 100 herbicides, but needed to be easily extended. Each weed required the same types of information. The same structure was true for herbicides. Large volumes of information needed to be collected and stored for display. Database storage had several advantages.

For the system as a whole:
- Information can be fed to both the modules and encyclopaedias from one source.
- Updating the database automatically updates both the system information and display information.

For individual encyclopaedic sections:
- The large volume of information can be broken into separate headings for storage and also for output.
- Data can be collected and stored at any time.
- Data are easier to check and validate.
- Missing data areas are easily identified.
- Display is independent of the data, if changes are made to the display it does not affect the data used and so reduces updating time, while editing.
- Changing information does not require change to the HTML code used for the display.
- Interactive searching of the data is facilitated.

The guide "Principles of Weed Management" is a single text so does not lend itself to database storage.

The encyclopaedia also displays information from the ArableDS data sharing environment (Parsons et al, 2005).

Data storage and use

The data were stored in an Access database. In addition to storing the collected data. each item has its source identified for traceability, attribution and validation. Information was stored with the removal of as much technical language as possible.

Storage and flow of encyclopaedic data is shown in figure 1.
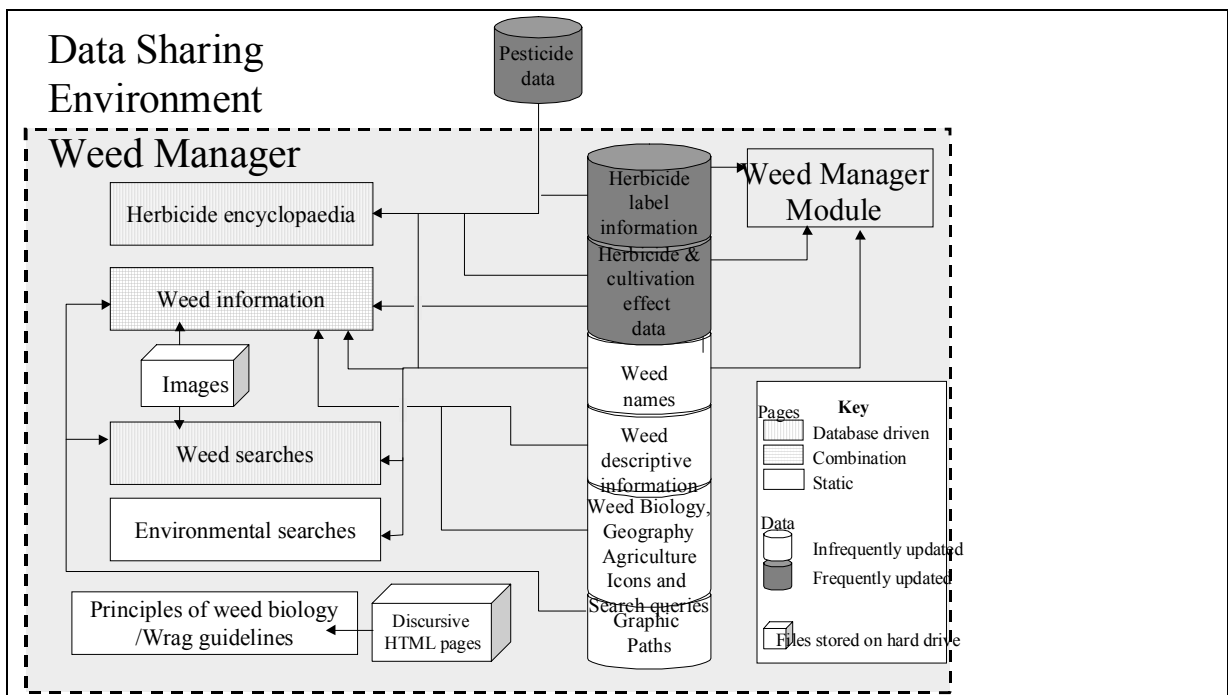
Figure 1: Storage and flow of information in Weed Manager and the ArableDSE.

There are two types of encyclopaedic data available; that used both by the Weed Manager modules (dotted lines) and the encyclopaedia (solid lines), and information only used in the encyclopaedia.

Some information feeds to one part of the encyclopaedia whereas other information is used by many parts of the system, for example, herbicide effect information feeds into both herbicide and weed information pages and also into the decision module.

The shading on the databases indicates the updating requirements. Similarly, the shading on the pages indicates the nature of the pages.

The weed information consists of over 60 different types of information such as descriptions, geographical locations and image files. In order to simplify data entry, validation and access, the data were split into separate tables with a common key. The key selected was the Eppo Code which is a five letter unique identifier of every vascular plant derived from the scientific name. The Eppo Code was used in the naming of all images simplifying the development of the encyclopaedia, and image source links.

Information display

The data stored in the database can be displayed in three ways; directly from the database; pages generated in advance, or a combination of the two methods. In all cases there is a balance to be struck.

Pages which are drawn dynamically (straight from the database) have a significant time penalty on loading, but require only one file change for updating. Pages that are stored as individual files will have an increased size for storage compared with the information stored only in the database but will load more quickly. Table 1 shows the page type and reason for choosing this for each part of the encyclopaedia.

Table 1: Encyclopaedic parts of the encyclopaedia.

Part of encyclopaedia	Type of page	reason
Herbicide information	Directly from database	Frequently updated + data used in the module
Weed information	Combination	includes weed - herbicide interactions which are frequently updated + data used in the module
Weed identification searches	Directly from database	Requires interactive queries
Principles of weed management	Static stand-alone pages	Essay style information
Environmental searches	Directly from database	Requires interactive queries

The pages with content drawn directly from the database use a specifically written component which isolates the files from the database, so that pages do not have to be rewritten if the database structure, information or the location changes.

User interface design
Simple rules were used in the design of the encyclopaedic interface:

     1. Sections and pages should be easily navigated.

     2. The section of the encyclopaedia being viewed should be clear (obvious location).

     3. Users should see as much information as possible without scrolling at 600*800 resolution and with minimal use of the mouse.

Navigation

The ArableDS browser displays an index so that navigation to any section of the encyclopaedia is simple. Links between pages and section are available as tabs or buttons on each page.

Location

The basic division of the encyclopaedia into product-related and weed-related information is marked by a change in livery, controlled by external stylesheets.

Information display

Information is presented in a card index format with almost all information visible on each card to reduce the need for scrolling,. Each card tab activates layers in the page to display relevant information and photographs. I have removed " " for consistency - if included should be single quotes ".

Some information is common to both the weed and herbicide pages and is displayed in the same way to help users navigate. For example, the information relating to the effect of herbicides and cultivations on weeds, which is used in the decision module, comes from the database and is displayed in both the herbicide and weed information pages in a similar format with colour coding used for emphasis. Extra herbicide efficacy information which has been collected for encyclopaedic use from papers and independent trials is displayed separately, but in the same format.

Implementation

The basic structure of each page type is simple HTML using javascript to hide and display page layers, and modify page information. When a page is loaded, all the information for that page is present, but only the most important is displayed with the rest on hidden layers.

Herbicide information

The herbicide encyclopaedia is fully database driven. There is only one file which allows a user to select herbicides. The data for the selected herbicide then populates the page. Users requested that the 10 most useful items of information should be immediately visible (Park, Parker and Ginsburg, 2004); these are displayed on the top layer. Hidden layers can be accessed at the click of a button.

Figure 2: Picture of the herbicide encyclopaedic page

Weed information

Weed biology information combines information generated in advance with database driven sections. Each weed has a separate file in index card format. Hidden layers are accessed by clicking the card index tabs. The herbicide and cultivation effects information are displayed in a pop-up window.

A dialog application was written to create static pages from a database. A template page was developed specifying the format of the new file, the location of the populating data in the database and the javascript required to display the herbicide effect information from the database and control the page dynamics. The output is a series of files, one for each Eppo code in the database.

It was not possible to remove all the technical language from the encyclopaedia so some explanation is necessary. Two mechanisms are used to provide these explanations. For each weed information page, tool tip style explanations are added to words and phrases in the encyclopaedia. A second dialog application was written to add tool tips to selected words and phrases in the html files. This allows the definitions to be stored separately from the basic data in a database table. The program searches for each glossary item in the text of a file and replaces the item with the required html and definition. All the terminology is also listed on a single glossary page

Figure 3: Picture of weed biology page

Weed identification searches

Weed searches presented a new design problem. There are various available keys for plants and weeds with common identification systems, which divide weeds into different classes and identify them by this class (i.e. Chancellor; 66, Hanf, 83). The botanical keys used in printed botanical guides usually identify plants by flower although some include mature plant stages, agricultural guides show early plant growth stages at which time weeds are usually controlled. Where keys are language based, botanical terms are often used, increasing the difficulty for non botanists.. Traditionally, users may have to make from 5- 20 decisions to identify the plant. In most botanical keys, one pathway through the key leads to the plant in question but this does not take user error into account. As a result they may discard the key, and instead skim through every possible picture before they recognise the plant. Electronic identification keys can have a "many to one" relationship, where, for example a cotyledon can be a member of several different sets of characters. (Figure 3).
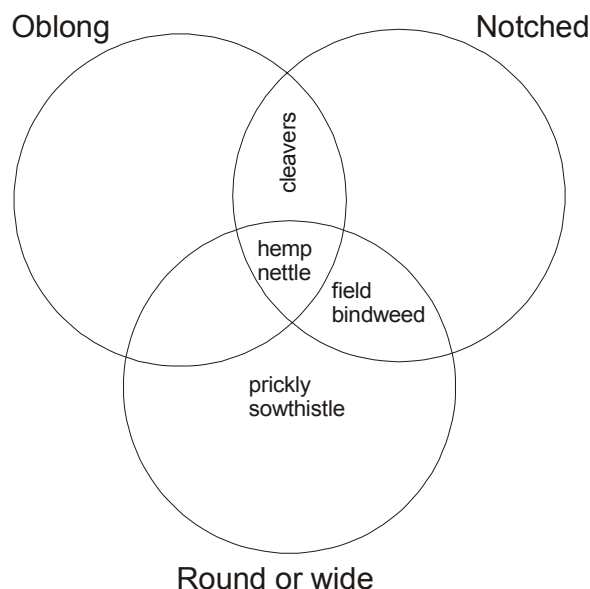
Figure 3. A leaf can be characterised by one or many sets, choosing one of the sets defined in Weed Manager will retrieve all the members of that set., even if they belong to other sets.

The number of options that can be displayed on a screen is limited and the users preferred fewer choices. The Weed Manager identification keys were designed to minimise the number of decisions and allow for overlapping sets. The first decisions, the type of weed (grass or broad-leaved), and the growth stage (young or flowering), have mutually exclusive classes and are made by clicking on the index card tabs which call the appropriate search interface page. Each page is populated with simple radio button or check box choices with a maximum of 7 categories (sets) from which to choose. These pages are database driven because they display the results of queries. The results are displayed as thumbnails, which link to the weed information pages.

Insert figure

Figure 4: The search page for young broad-leaved weeds

A simple guide to weed management

The Principles of Weed Management includes background information on weed biology, soils, weed control in conventional and organic systems, and access to the WRAG guidelines (herbicide resistance management), and biodiversity. There are guides to growth stages of wheat, grasses and broad-leaved weeds, and pictures showing the number of weeds which give 5% yield loss in winter wheat. This was included to increase the users' confidence in the data they were entering into the mathematical modules which leads to greater confidence in the output. Each section of the principles is a single static file.

Insert figure

Figure 5: The simple guide to weed management

Environmental searches

Weed Manager contains a search to enable users to find weeds with particular environmental characteristics such as support for farmland birds (a prime environmental indicator), butterflies and rarity. This was a late requirement so was developed as a static page, but it should be converted to a database driven page in the future. This information is also displayed as icons in the decision module and weed information pages.

The Environmental search page uses select controls to output lists of non-crop plants in any particular environmental category, with links to the relevant weed information page.

Insert figure

Figure 6: An environmental search

User feedback

Weed Manager was reviewed by users in 2004 (HGCA reference). Users were very positive about the design of the encyclopaedia and found it intuitive and easy to find the information they required. The encyclopaedia and the module are seen as complementary sources for information on weed control.

Conclusion

Although the Weed Manager encyclopaedia has met the defined user needs, it is still being reviewed and updated to reflect changing needs and interface problems. Developers continuously monitor user-feedback for incorporation into future editions.

The database driven pages are slow to load, at present this is met by showing the proportion of information gathered with a progress bar. While reducing worry about loading, this does however slightly increase page loading time. Further work needs to be done to speed up these pages.

The security patch update for windows XP has also presented problems to naïve users, by blocking the dynamic pop up windows. The solution to this problem will require some design changes.

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(Draft paper version 3 on 02/12/05)
A model to simulate the growth, development and competitive effect of weeds in a winter wheat crop in the United Kingdom.

L. R. Benjamin, P J Lutman, J. Cussans, J. Storkey

Introduction

The decision whether to control weeds, and what weed control measure to choose, is often a complex trade-off between likely economic impact of the weeds at the density and size present, the cost of weed control measure and the efficacy of the weed control measures, given the growth stage of the weeds. Many attempts have been made to attempt to quantify this trade-off by developing growth, development and competition models. Simple empirical relationships relating crop yield loss to weed density has been developed (Cousens, 1985) and this has been developed to relate yield loss to the early relative leaf areas of weeds and the crop (van Acker et al., 1997). More complex ecophysiological models have been developed, which are able to take a more mechanistic approach to simulating weed – crop competition (Kropff and van Laar, 1993).

Several decision support systems for weed control have been developed from these models, for example (Hoffman et al., 1999) (need to check this paper, I do not have a reprint!!). The effects of tillage on *Amaranthus* species seedling emergence have been simulated with the intention of incorporating the emergence models within ecophysiological growth and competition models for decisions on weed control (Oryokot et al., 1997). A decision support system (WHEATMAN) for was developed to take account of the specific conditions for Australian wheat growers (Woodruff, 1992). In this model, weed infestation was only one of several environmental factors affecting wheat productivity. A GIS-based decision support software has been developed to aid weed control in developing countries (Zesheng and Ling, 1997). This approach included a database of herbicide activities and dose-response curves for various weed species. The decision support software produced a herbicide spray map. Weed management decision models have been perceived as having mainly an educational value rather than as a tool for making specific strategic or tactical decisions (Wilkerson et al., 2002). Decision support software may be perceived as too simple; not taking into account all the factors that influence the interaction between crop and weed, or ignoring all the factors that growers need to consider in crop husbandry. Decision support can also be considered too complex, requiring information that is difficult or impossible to obtain in commercial practice (Wilkerson et al., 2002). To date, no decision support software has been developed for crops grown in the United Kingdom.

In this paper the models that lie behind a new decision support system, WMSS are described. WMSS is a **W**eed **M**anagement **S**upport **S**ystem, intended to support strategic decision for weed control in winter wheat crops in the United Kingdom. This paper deals with the methodology of the biological models that simulate weed and crop growth within a growing season. A complementary paper will describe the population dynamics of weed species through a crop rotation which includes winter wheat crops. The models described in the paper have been calibrated for the following weeds; black-grass, chickweed, cleavers, wild oat, barren brome, Italian ryegrass, annual meadow grass, fat hen, poppy and knotgrass. Also, the following two crops that act as volunteer weeds were parameterised; winter oilseed rape and field beans.

WMSS is part of the suite of models that take advantage of the DESSAC platform. This allows the advantage that many features of a site, such as soil type, meteorological data, and features of herbicides, and be accessed from the DESSAC platform.

Description of the Within Season Model
Climate and Astronomical Data
Calculation of day length is based on time of year and latitude, using the ASTRO procedure (Kropff and van Laar, 1993). The duration of the photoperiod was calculated as for day length, but assumed that the start and end were determined when the sun was 6 degrees below the horizon.

Maximum and minimum temperatures, radiation, rainfall, evapotranspiration from a reference crop were collated from a range of sites across the United Kingdom ((Parsons et al., 2004)). For any one site and season these data records were retrieved from 1st of January of year of drilling to 31st December of the year of harvest. Daily day degrees were calculated based on integrating the area above the base and a diurnal sine curved around the maximum and minimum temperatures (refer to appendix to write out full set of equations).

Seedling establishment
Seasonality of Emergence and Soil Water
For most weed species seedling establishment is confined to periods of the year, even when temperature and soil moisture are adequate for establishment at other times of the year. This seasonality of establishment has been described for several weed species by (Roberts and Feast, 1973). The numbers of seedlings established in each month of the year was read off the graphs of seasonality and tables of establishment for *A. myosuroides*, *Avena fatua*, *Chenpodium album*, *G. aparine*, *Matricaria matricoides*, *Papaver rhoeas*, *Poa annua*, *Polygonum aviculare* and S. *media* from the Weed Control Handbook (1990), for *Capsella bursa-pastoris*, *Euphorbia helioscopia*, *Fumaria officinalis*, *Fallopia convolvulus*, and *Veronica hederifolia* from (Roberts and Feast, 1973) and *Anisantha sterilis* from (Froud-Williams, 1983).

For each species, the numbers establishing each month were expressed as a proportion of the maximum number of seedlings emerging in the year. These numbers of seedlings emerging on any one day are a function of the dormancy of the seeds and the soil water and temperature regime. To quantify the extent of seed dormancy, it was necessary to allow for any effects that soil moisture and temperature may have had on the seasonal emergence patterns reported by (1990; Froud-Williams, 1983; Roberts and Feast, 1973). The influence of soil moisture on seasonal emergence was assumed to have been obscured by the use of data from several years. Although soil moisture is likely to be lower in summer, sporadic rainfall may produce periods in the summer when soil moisture is higher than in some periods in the winter. Hence, it was assumed that soil moisture had a negligible effect on the seasonal emergence patterns reported.

Although there are sporadic fluctuations in temperature throughout the year, the soil temperature in summer can be assumed to be never lower than that in winter. A means of adjusting the reported seasonal emergence patterns for soil temperature was sought by examining the seasonal emergence of *P. annua*, which has no dormancy. Hence, for this species, the difference between numbers emerging in different months could be attributed entirely to soil temperature. More explicitly, for each month, the ratio of emergence of *P. annua* in July (the month with the greatest emergence) to the monthly emergence was taken as a weighting factor to apply to the monthly emergence of each other weed species, to render the emergence pattern independent of soil temperature.

For each weed species, the numbers emerging each month were adjusted by the *P. annua* weighting factor, and these numbers summed for all twelve months of the year. The numbers emerging in each month were then scaled as a proportion of the total numbers emerging over the entire year.

The accumulated scaled and *P. annua* adjusted monthly emergence values for each species were calculated, *n*. A cubic polynomial fitted was fitted to *n* for each species. Hence,

$$n_t = a + b.t + c.t^2 + d.t^3 \qquad\qquad 1$$

where *t* is the day of the year.

The rate in change in the value of *n* is a measure the daily dormancy value of the species. That is, where the change in cumulative numbers of seedlings appearing is great, then the dormancy must be low, whereas where the cumulative numbers remains constant with time, then dormancy must be high.

By differentiating eqn 5, the rate of change in cumulative numbers, dn_t/dt, is given by

$$dn_t/dt = b + 2.c.t + 3.d.t^2 \qquad\qquad 2$$

The value of dn_t/dt was calculated as a proportion, S, of the maximum value of dn_t/dt, so that on any day the value S varied between 0 and 1. The value of S was used in eqn 3 to calculate the value of D_m.

Temperature-Driven Seedling Emergence

For the each species, the accumulated number of seedlings emerged, n, at any site s on day t is described by a logistic equation, based on thermal time.

$$n_{s,t} = A + C_s/(1 + \exp(-B.(X_t - M))) \qquad\qquad 3$$

where X_t is the accumulated day degrees, modified by the seasonality and moisture limitation, above a base temperature T_b from the sowing date to day t. A is a number of seedlings present at $X_{t=0}$, and $A + C$ is the maximum number of seedlings to establish, and varies between sites and years. M is the duration to the inflexion point of the logistic curve and B is the slope of the curve at the inflexion point.

The seedling emergence counts used for fitting eqn 3 were for winter wheat (*Triticum aestivium*), black-grass (*Alopecurus myosuroides*), cleavers (*Galium aparine*), and chickweed (*Stellaria media*), recorded at six sites in the England in one year and five of these sites in the subsequent two years, giving a total of 16 site/year combinations (Ingle et al., 1997).

Differences between species in observed seedling emergence patterns were not great (Table 1, Figures 1, 2, 3 and 4). Wheat was the fastest species to emerge with a mean emergence date of 33 days after sowing, with a range of 8 to 89 days. Cleavers was the slowest with a mean emergence date of 40 days with a range of 14 to 98 days.

Initially when fitting eqn 3, A, C, B, M and T_b were determined by fitting eqn 3 to seedling emergence counts using a Nelder – Mead unconstrained minimisation procedure, called FMINSEARCH (Matlab, 1996). The estimated values of T_b were often unreasonable low (of the order of -40°C), and it was concluded that the range of temperatures during the experimental period were not sufficiently broad to allow this parameter to be estimated accurately from the data. Consequently, the value of T_b was set at 0°C and the dormancy modified day degrees for each species were calculated from sowing to each of the seedling counts.

Eqn 3, was fitted to each species separately using the FITCURVE directive of Genstat (Genstat, 2002). First of all, with the value of T_b fixed at 0, and the accumulated effective day degrees for each of the species was calculated from crop sowing each of the seedling emergence recording dates. For each species common values of B and M (Table 2) were estimated over all the datasets, but A and C were allowed to vary with site – year combination. The agreement between observed and fitted data was generally close (Figs 1, 2, 3 and 4). The fitted lines were sometimes not smooth because the driving variable for eqn 3 is day degrees modified by the dormancy, which varies with day of the year and species. The data in the figures are plotted against days after sowing, as this is more meaningful a scale than day degrees. It may seem odd that the value of M for wheat is greater than that for any of the weed species (Table 1). This is because given the dormancy that occurs within the species, there is no close linkage between chronological time and time on a day degrees basis.

Within WMSS, emergence of winter wheat is simulated as a single cohort of seedlings emerging M day degrees after drilling. The density of seedlings in this cohort is taken as the average of the range specified by the user.

The simulation of weed emergence with WMSS is more complex. Each weed species emerges as eight cohorts of seedlings. The number of seedlings in each cohort is calculated as an eighth of the average of the density range specified by the user. Furthermore, the accumulation of thermal time

for progression to germination and emergence is modified by daily soil moisture and seasonality of establishment factors. The stimulus for establishment is in reference to the date of drilling for one of the cohorts and to the date that the previous crop was harvested for the remaining seven cohorts.

For the cohort whose establishment is in reference to drilling, germination occurs on the drilling date and establishment occurs after 80 modified day degrees have accumulated.

For the other cohorts, the accumulated modified day degrees, $\hat{X}_e$, when a proportion f of the population has emerged can be obtained by re-arranging eqn 1.

$$\hat{X}_e = (M.B - log((1 - f)/f))/B \qquad\qquad 4$$

The values of $\hat{X}_e$ that corresponds to values of f of 0.125, 0.250, 0.375, 0.500, 0.625, 0.75 and 0.875 were calculated, and assigned to the day degree requirement for emergence of cohorts one to seven, respectively. The germination requirement was calculated as $\hat{X}_g = \max[\hat{X}_e - 80, 0]$ for each cohort.

The dates of seedling germination and emergence from either the drilling date or date of the previous harvest was determined when the accumulated modified day degrees exceeded the germination and emergence requirements, calculated from eqn 2.

On each day, the day degrees, D_m, were calculated as

$$D_m = D.\psi.S \qquad\qquad 5$$

where D is the day degrees above a the base temperature (calculated based on a diurnal sine curve fluctuation between the maximum and minimum temperatures), ψ is a term for soil water content and S is a term for the seasonality of seedling establishment.

It was assumed that the soil after harvest or drilling is initially dry and the value of ψ was set to 0. On each day, t, a running rainfall total, R, was calculated, with the total incremented by rainfall, r, and subtracted by evapotranspiration, E. The running total was not allowed to fall below zero or exceed 20 mm.

$$R_t = R_{t-1} + r_t - E_t$$
$$R_t = \max[R_t, 0] \qquad\qquad 6$$
$$R_t = \min[R_t, 20]$$

If R_t exceeded 5, then ψ was set to 1.

Phenology

For graminaceous weeds, the decimal code scale of development for cereals was adopted (Zadoks et al., 1974). The progression of development along the decimal code was based on thermal time modified by vernalisation and photoperiod effects. An accumulated photovernal thermal time (PVTT) was calculated for each cohort of each species (Milne et al., 2003). The Zadoks values for the plants from anthesis to maturity were identical to that of Milne *et al.* (2003), but their paper dealt only with the timing of appearance of culm leaves and ear maturity, because their model was targeted at disease control on the upper canopy. The model by Milne *et al.* (2003) used the timing of anthesis and the calculation of the phyllochron as a reference point for the production of the culm leaves. The phyllochron ρ, was related to the rate of change of day length by

$$\rho = \frac{1}{\alpha + \beta R} \qquad\qquad 7$$

where α and β are parameters, and R is the rate of change of day length on the day of plant emergence, t_e (with 1st January equal to 1). The value of R was approximated by

$$R = \frac{10\pi}{365} \cos\left(2\pi \frac{(t_e - 444)}{365} \right) \qquad\qquad 8$$

Growth stage 0 was achieved on the date of germination, and the growth stage, Z, on any date, t, from germination to emergence was given as

$$Z = 10.\frac{\sum\limits_{i=t_g}^{i=t} D_i}{\sum\limits_{i=t_g}^{i=t_e} D_i} \qquad\qquad 9$$

where D is day degrees.

After emergence, the value of Z remains at 10 until the first leaf is formed. A new leaf was assumed appear when the accumulated day degrees from the appearance of the previous leaf had exceed the value of the phyllochron, ρ. On the appearance of a leaf, any difference between the accumulated day degrees and ρ was not lost, but contributed to the accumulation of day degrees for the appearance of the next leaf. The values of Z increased from 11, 12, 13 … 19 with the appearance of first, second, third … and ninth leaves, respectively on the entire plant. The value of Z remains at 19 when there were nine or more leaves present. In practice values of Z greater than 13 or 14 are never utilised, because once the tillers appear, the value of Z was increased from 21, 22, 23 … 29 with the appearance of first, second, third … and ninth tillers, respectively on the entire plant. The progress towards tillering is assumed to occur when a set number of phyllochrons, Φ, have been produced from emergence. Also, secondary and higher order tillers start to be produced once Φ phyllochrons have elapse since the initiation of the mother tiller. Tillers are produced once the accumulated thermal time exceeds the phyllochron for tillering, ϕ_T. The processes of leaf production, and tillering continue until main stem extension, Zadoks 30, which is calculated as a fixed number of phyllochrons before the time of anthesis (Milne et al., 2003).

For broad-leaved weeds, a similar approach is taken. The calculation of germination and emergence time is identical in approach as that for graminaceous weeds. The subsequent growth stages are based solely on the number of leaves on the entire plant. Unlike graminaceous weeds, the equivalent of tillering (that is branching) does not directly affect the growth stage code. Branching, however, is simulated in an identical process to tillering, so that a correct number of leaves on the entire plant is estimated. One further difference is that the number of leaves produced per phyllochron may be more than one. For *G. aparine*, each whorl of leaves is treated as though it is a single leaf.

Crop Yield Loss
The estimation of crop yield loss is based on a mixture of a complex eco-physiological model and a simple empirical static yield loss equation. The underlying principle is to allow the entire community of plants to increment in green area to the point of canopy closure. The ratio of individual weed species green area to the sum of the crop and individual weed species leaf area is used to estimate the crop yield loss associated with that species.

The growth of each species in the community from emergence to canopy closure is simulated using the ecophysiological model of (Kropff and van Laar, 1993). The initial green area index (GAI) of each cohort of the weed and that of the crop is based on the green area per seedling at the time of full hypocotyls or cotyledon expansion and the density of the cohort or of the crop.

Where this initial seedling green area is not known, then for grass species, the value is estimated as the product of the green area per black-grass seedling (0.000035 m^2) and the ratio of the species seed weight to the seed weight of black-grass (1.1 mg). For broadleafed species, the initial green area is estimated as the product of the green area per chickweed seedling (0.000031 m^2) and the ratio of the species seed weight to the seed weight of chickweed (1.1 mg).

The simulation commences on the date of emergence of the first cohort of the weed or the crop (which ever is the earliest), and the simulation allows the inclusion of further weed cohorts as the simulation proceeds. The simulation ends when the GAI of the entire community equals 0.75, which is taken as the point of canopy closure. The yield loss associated with a species is calculated as

$$Y_L = \frac{Y.q.L_w}{1 + (q - 1).L_w} \qquad\qquad 10$$

where Y is the crop yield in weed-free conditions, q is the damage coefficient constant specific to the combination of crop and weed species and L_w is given by

$$L_w = \frac{GAI_{weed}}{GAI_{weed} + GAI_{crop}} \qquad\qquad 11$$

(Kropff et al., 1995). Note, that the value GAI_{weed} is the GAI summed over all the cohorts of the weed species present at the time of canopy closure. The weeds are assumed to act independently of one another, but the summated yield losses were not allowed to exceed weed-free crop yield. This assumption removed the necessity to simulate weed-on-weed interactions. In most commercial conditions, weed densities are sufficiently low to render these interactions to be of no biological importance, although they can be considerable in experimental circumstances.

Weed Control Measures

Herbicides and mechanical cultivations are assumed to destroy the GAI of the weeds, with an efficacy that varies with weed species and weed growth stage. For the purposes of WMSS, grass weed growth stages were grouped into the following nine categories of Zadoks values, 0-7; 8-10; 11-13; 14-21; 22-29; 30-31; 32-39; 40-45 and 46-93. Broadleafed weed growth stages were grouped into the following six categories, pre-emergence; cotyledons – two leaves; two – four leaves; four – six leaves; six leaves – eight leaves; more than eight leaves to flowering. Note that the flowering growth stage will take precedence over the vegetative growth stages if flowing occurs sooner than eight leaves.

The proportion of GAI lost due to cultivations or herbicides (hereafter called 'product') was grouped according the following levels as, 0.00 for certain growth stages, where weeds are immune to weed control such as weed pre-germination; 0.01 for weeds resistant to a product, or a product of unknown efficacy; 0.51 for weeds moderately resistant to a product; 0.76 for weeds moderately sensitive to a product; 0.91 for weeds sensitive to a product; 1.00 for herbicidal sprays applied to emerged weeds pre-crop emergence.

Each weed species, growth stage and product combination was assigned a level of proportional kill (D. H. K. Davis, personal communication). This level of control was assumed to be unaffected by the cohort number of the weed species.

A programme of cultivations and sprays was considered by calculating the efficacy of each spray and cultivation. Let $\xi_{s,i}$ be the percentage control of cohort i of product s as determined by the growth stage of the cohort at the time of product application. Hence, the survival is given by $1 - \xi_{s,i}$. For a spray program of M products, then the combined survival of cohort i is given by the multiplicative survival response model, $\prod_{s=1}^{s=M}(1 - \xi_{s,i})$. The proportion of cohort i controlled, C_i, by the spray

program is given by $1 - \prod_{s=1}^{s=M}(1 - \xi_{s,i})$. For the entire species, containing n cohorts, the percentage control, K, is given by

$$K = \frac{\sum_{i=1}^{i=n} G_i.C_i}{\sum_{i=1}^{i=n} G_i}.100 \qquad\qquad 12$$

where G is GAI at the time of canopy closure. Hence, a feature of WMSS, is to calculate the proportion of the erosion of GAI according to the growth stage of the weed at the time of the application of the product. The next assumption is that this erosion of GAI occurs at the time of canopy closure. This assumption may appear odd, but it has important implications for reducing the number of calculations, which is particularly important when different spray programmes are being compared by the optimisation model within WMSS. This assumption means that the complex dynamic ecophysiological model to calculate the species value for G need be run only once at the outset with a control cultivation programme that is sufficient only to establish the crop.

Cultivations can stimulate the emergence of weed seedlings (Vleeshouwers and Kropff, 2000). This breakage of dormancy is due to complex physiological processes that have not yet been successfully simulated (Vleeshouwers and Kropff, 2000). In WMSS, an empirical approach is taken, in which the stimulation of weed emergence is handled relatively empirically, with the emergence date of cohort number seven being advance to emerge 80 modified day degrees after the first cultivation. In effect, the assumption within WMSS is that delay in emergence of cohort seven is due to a dormancy mechanism that is broken by soil disturbance.

Ploughing is treated differently to other cultivations. This is because whereas other cultivations disturb the soil, ploughing inverts the soil profile. In effect, ploughing replaces the soil seedbank in the soil layer from which weed seedlings can establish with a new soil seedbank. WMSS assumes that the entire soil profile weed seedbank is so large that the new seedbank in the shallow layer after ploughing is just as great as the pre-ploughing one. The impact of ploughing id to delay the emergence of cohorts one to seven to be with reference to the date of ploughing rather than with reference to the date of the last harvest.

Observations
An important feature of WMSS, is that users can provide observations of the crop and/or weed, which will adjust the simulation results to current circumstances. Observations of growth stage, cover and density can be entered.

Growth stage observations are handled by comparing the growth stage that the user is specifying for a weed on a date with the growth stage that is currently calculated for the most precocious cohort. The growth stages of all the cohorts is advanced or retarded by the difference in time between the observed and currently expected values.

Wheareas WMSS deals with GAI, users are more likely to be able to observe percentage ground cover. Hence, the first action when dealing with a cover observation is to convert it to a GAI value. The simple conversion, GAI=0.0278.percentage ground cover. The equation is robust up to 5 percent ground cover (J. Storkey, personal communication).

The procedure within WMSS is to calculate the ratio of the summed GAI for all cohorts of a species expected at the date of the observation to the GAI observed for the species. In calculating the expected GAI any potential reduction in GAI due to weed control measures are included in the simulation from emergence of the first cohort to the date of observation. The ratio of observed to expected GAI is used as a factor to multiply the green area per seedling at the time of emergence.

Hence, if the observed GAI is twice that which would be expected, then the entire wmss model is run gain with the GA at emergence being inflated by the discrepancy between emerged and expected GAI.

Table 1. The difference between the expected and observed days after sowing to achieve the observed numbers of seedlings

| | Species | | | |
	Wheat	Black-grass	Chickweed	Cleavers
mean observed days after sowing	32.9	34.3	34.5	39.5
first observed day after sowing	8	10	9	14
last observed day after sowing	89	89	98	98

Table 2. Value of parameters B and M from eqn (1) for wheat, black-grass, chickweed and cleavers, fitted to the seedling emergence data from (Ingle et al., 1997) ± standard error.

| | | Species | | |
Parameter	Wheat	Black-grass	Chickweed	Cleavers
B ($^{o}C^{-1}$)	0.0174±0.00280	0.0261±0.00388	0.0263±0.00293	0.0228±0.00252
M (^{o}C)	159±9.4	112±3.9	103±4.0	142±6.9
number	138	150	144	156

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Legend For Figures

Figure 1. The relationship between number of black-grass seedlings emerged and days after sowing of (a) Boxworth, (b) Bridgets, (c) Drayton, (d) High Mowthorpe, (e) Rothamsted and (f) Woburn (Ingle et al., 1997). Symbols are the observed counts and the lines fitted by Eqn (3) with common values of B and M but different values of C and A between years and sites. Circles and solid line for 1994-5, squares and dashed line for 1995-6 and triangles and dotted line for 1996-7.

Figure 2. The relationship between number of chickweed seedlings emerged and days after sowing of (a) Boxworth, (b) Bridgets, (c) Drayton, (d) High Mowthorpe, (e) Rothamsted and (f) Woburn (Ingle et al., 1997). Symbols are the observed counts and the lines fitted by Eqn (3) with common values of B and M but different values of C and A between years and sites. Circles and solid line for 1994-5, squares and dashed line for 1995-6 and triangles and dotted line for 1996-7.

Figure 3. The relationship between number of cleavers seedlings emerged and days after sowing of (a) Boxworth, (b) Bridgets, (c) Drayton, (d) High Mowthorpe, (e) Rothamsted and (f) Woburn (Ingle et al., 1997). Symbols are the observed counts and the lines fitted by Eqn (3) with common values of B and M but different values of C and A between years and sites. Circles and solid line for 1994-5, squares and dashed line for 1995-6 and triangles and dotted line for 1996-7.

Figure 4. The relationship between number of wheat seedlings emerged and days after sowing of (a) Boxworth, (b) Bridgets, (c) Drayton, (d) High Mowthorpe, (e) Rothamsted and (f) Woburn (Ingle et al., 1997). Symbols are the observed counts and the lines fitted by Eqn (3) with common values of B and M but different values of C and A between years and sites. Circles and solid line for 1994-5, squares and dashed line for 1995-6 and triangles and dotted line for 1996-7.

Fig. 1

a)

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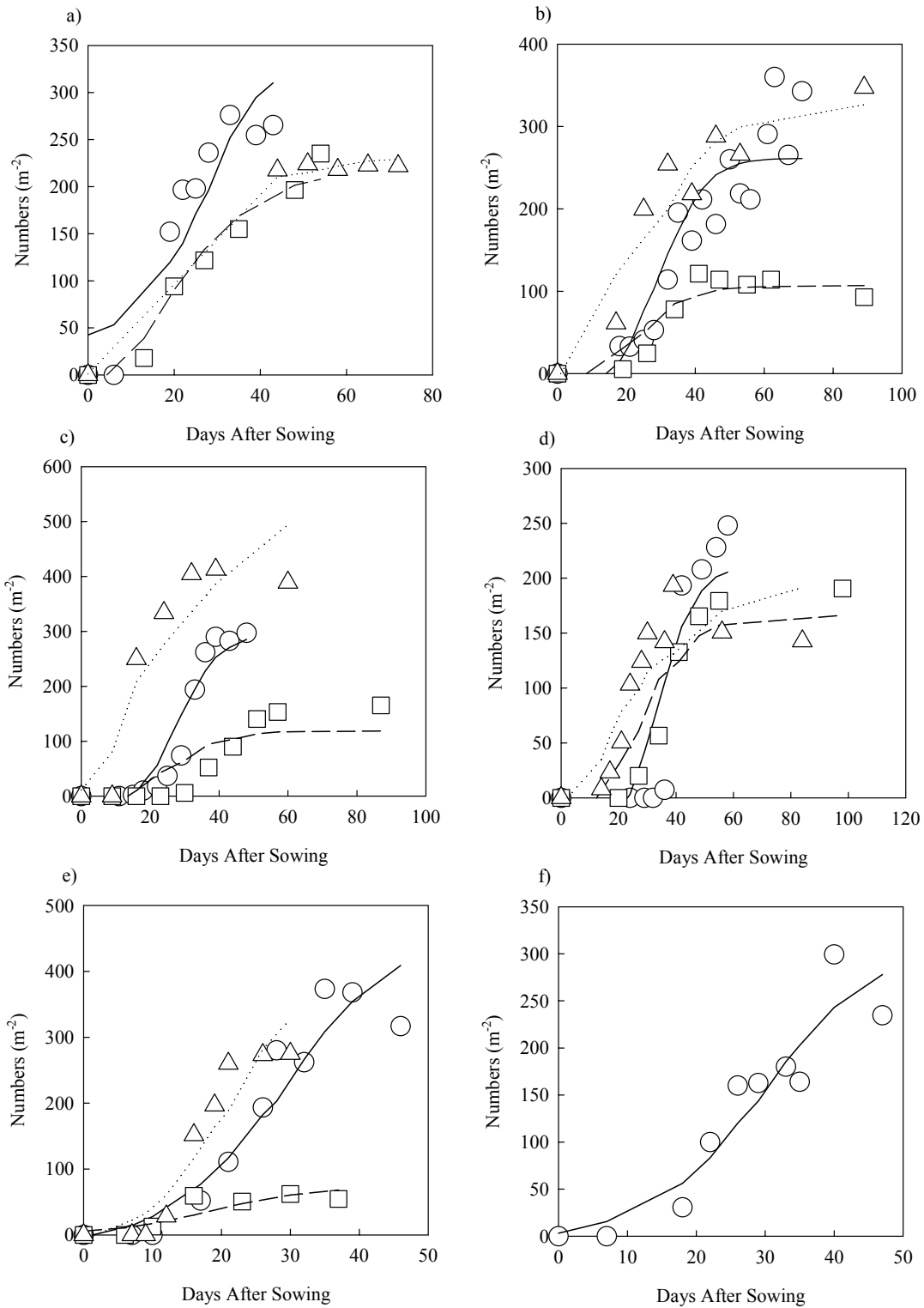
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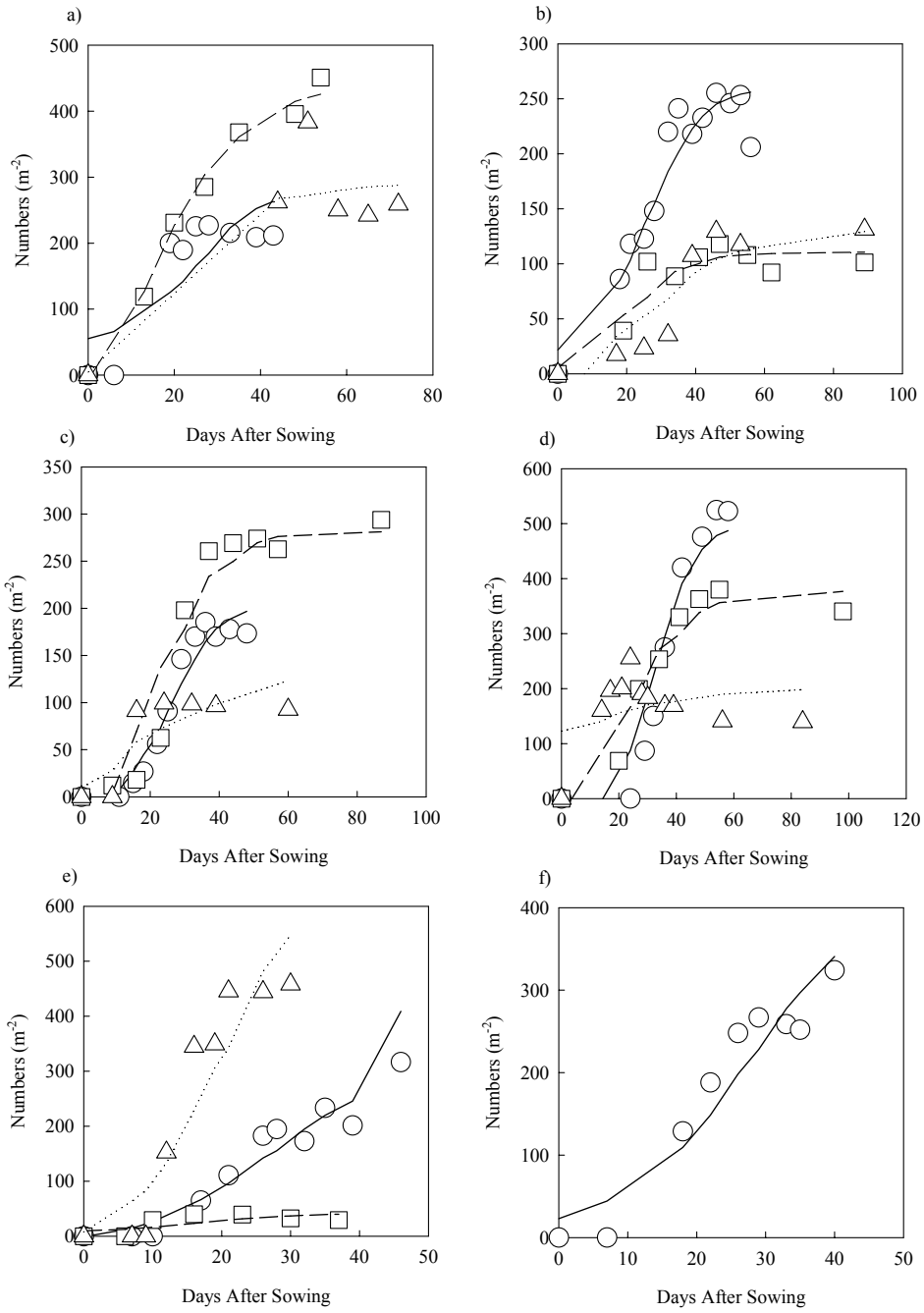
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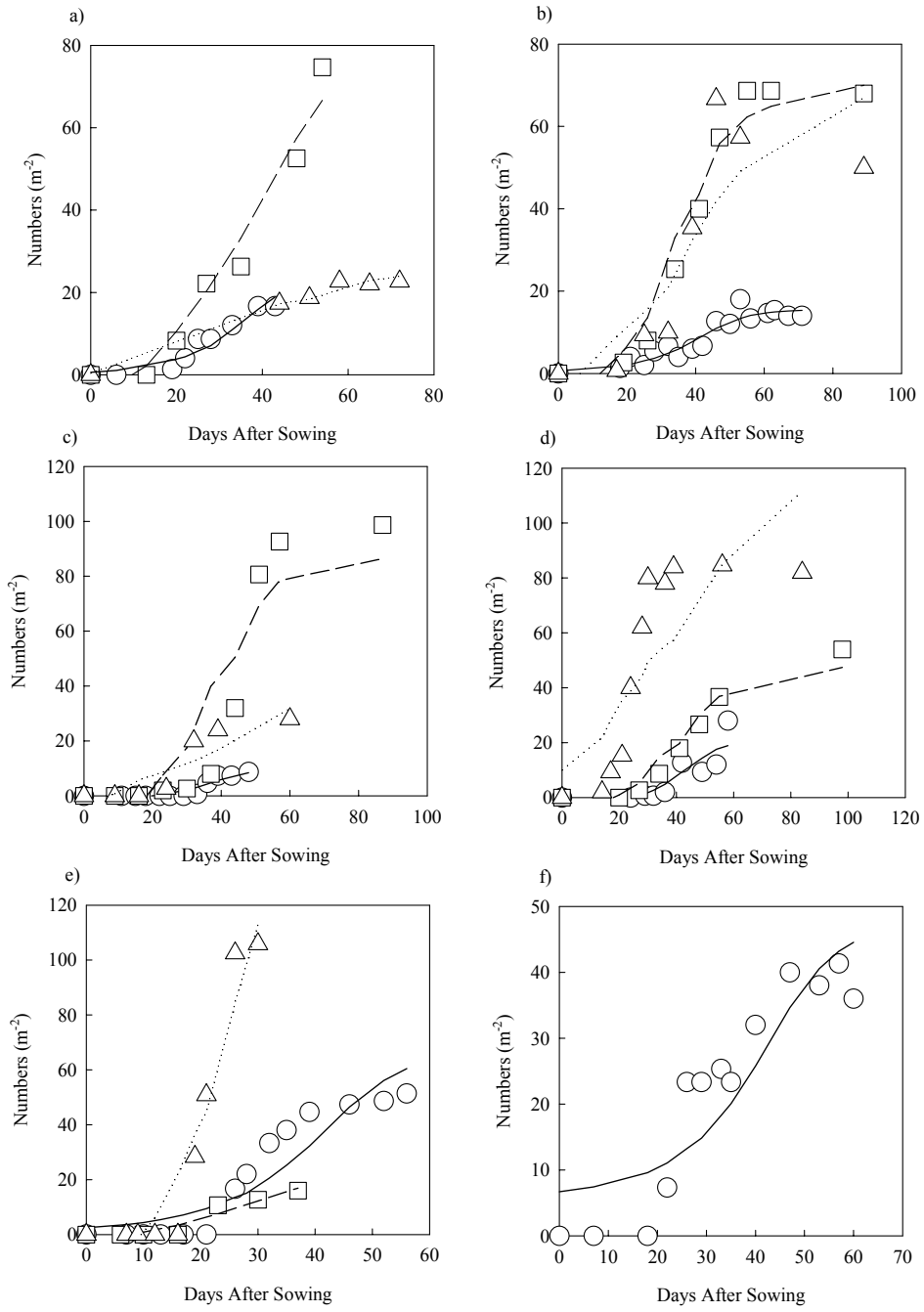
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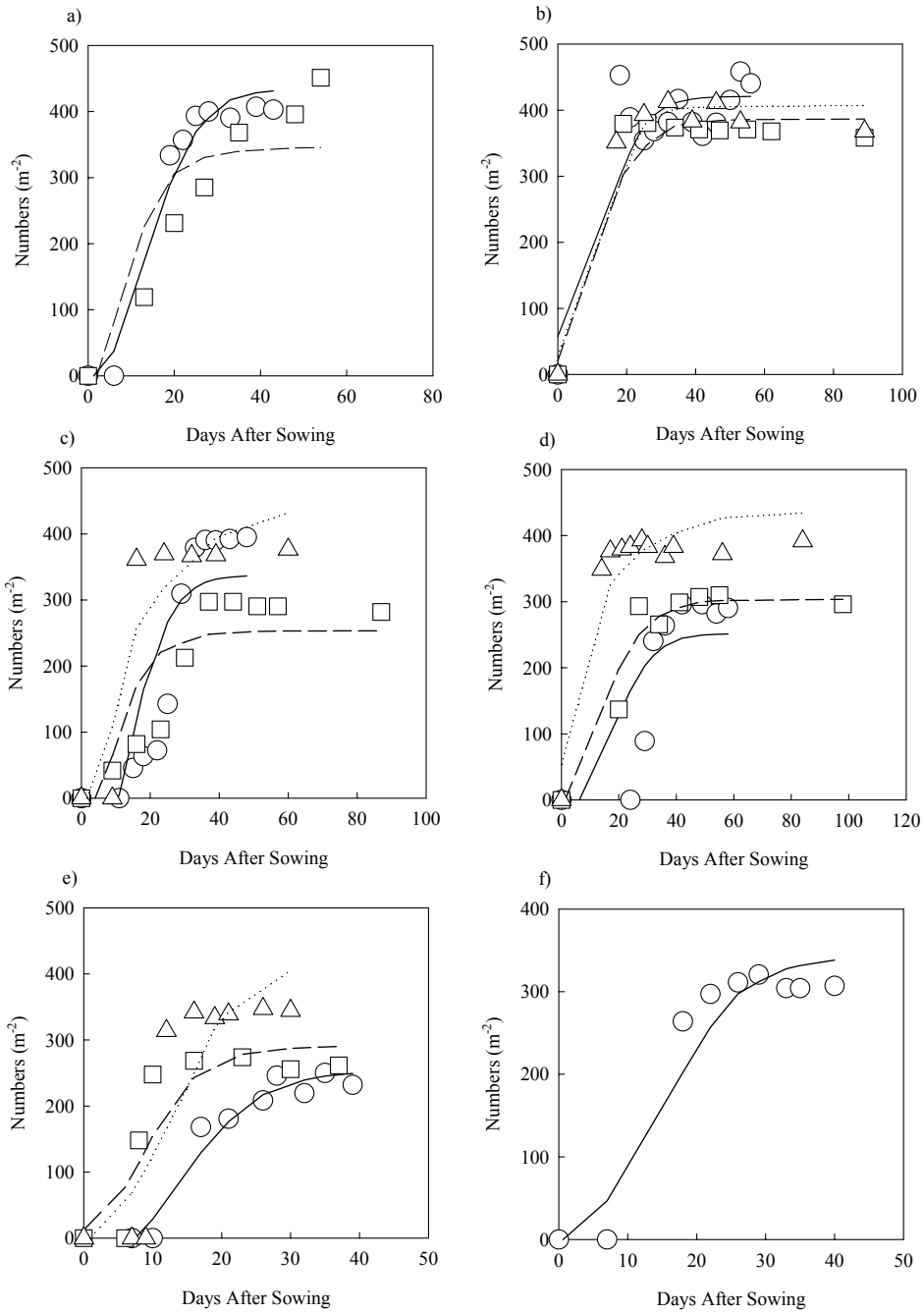
Modelling weed management over a rotation in the UK using stochastic dynamic programming

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Short title: *modelling weed management over a rotation*

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Introduction

Weed control in UK arable crops is an expensive necessity for all arable farmers. The survey of pesticide usage in Great Britain in 2002 shows that on average herbicides were applied to wheat on 2.8 occasions, included 4.3 products and 5.3 active ingredients. 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 effective. An approach to weed control based on consideration of crop rotations is therefore likely to be more successful in the long term. By carefully planning the future rotation and cultivations, the weed seedbank, which controls the weed infestation level in the crop can be kept to a manageable level.

Although a number of groups have developed models that endeavour to advise on within season weed control (Berti *et al*., 2003; Neeser *et al*., 2004; Bennett *et al*., 2003), much less attention has been paid to rotational weed management. The model presented here simulates changes in weed seedbank density (seeds m^{-2}) from season to season given crop, sowing time, cultivation and herbicide control. Yield loss due to weeds is estimated in each season, and the associated margin calculated. This allows the effect of control strategies to be assessed in both terms of seedbank density and margin. Once the model is constructed, one is still faced with the question – given a certain size seedbank, what sequence of actions will give the best long term profit? The answer to this may not be straight-forward because controlling a weed in the current season may not give immediate financial reward, but could help avert uncontrollably high weed densities in a future season. The stochastic dynamic programming method (Howard, 1960) is ideally suited to solve problems of this type. It analyses a system and evaluates a strategy for each system state to maximise future rewards. In the case discussed here, the system is the weed population dynamic model, the system state is the seedbank density (seeds m^{-2}), the strategy specifies crop, sowing time, cultivation and herbicide choice, and the reward is made up of future profit margins.

The model and dynamic programme were developed as part of a 'rotational' module within a decision support system for weed control in the UK (Collings *et al*., 2003). This decision support system is called Weed Manager (formerly Weed Managment Support System or WMSS) and it would be run on a personnel computer. Weed Manager is currently being parameterised for 12 common annual weed species, and was designed so that the user selects a subset of weed species that are most important in the selected field. They can then choose either to run the model for a 6 year time period choosing their own crop, sowing time, cultivation and herbicide control settings in each season, or ask the system to suggest a forward plan which gives the best profit margin. In both cases, the system presents the result of the actions both in terms of changing seedbank population and in terms of profit margin. Weed Manager is designed so that this rotational module runs alongside a 'within season' module that estimates in some detail the yield losses caused to winter wheat in any one growing season by alternative cultural and chemical management tools.

The rotational module is based on the life cycle model developed by Moss (1990) for *Alopecurus myosuroides* Huds (black-grass), 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 *Avena fatua* L. (wild oats) respectively. These consider the soil to have a deep and shallow layer, and they track the changes in the seedbank in each layer. Seeds migrate between layers when cultivations are applied. Seedlings emerge from the shallow soil depth and are killed to variable degrees by the weed control practices. Surviving plants produce seeds that are returned to the soil seedbank in the shallow layer. These two state variables (shallow and deep seedbank) drive the change in the weed population through the rotation as modified by a series of management influenced parameters. Because of the large uncertainties present in many of the steps outlined above, it is necessary to describe them by probability distributions, leading to a *stochastic* model.

Sells (1993, 1995) modified these later two models for use in a stochastic dynamic programme (Howard, 1960) which calculated the optimal strategy for controlling *A. fatua* and *A. myosuroides*. Because the memory requirements for a dynamic programme increase exponentially with the number of state variables ("the curse of dimensionality") it was necessary to simplify the model to contain a single soil layer only. For the present system, it was decided that it was essential to include two layers (shallow and deep), so that the impact of alternative cultural practices on seed distribution in the soil could be modelled. By using slightly fewer discrete states for the seedbank in each layer than Sells, and given the increases in computing power available, it was found to be possible to solve a two-layer model for up to two weed species in an acceptable time. The method used to handle larger numbers of species will be discussed below.

Materials and methods

The Dynamic Program Formulation

The formulation of the stochastic dynamic program is

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

where $f_t(i)$ is the optimal expected financial reward for years t and beyond given that the system state is i at the beginning of year t. In this application the system state describes the number of seeds in the seedbank. The transition probability of going from state i to j given a strategy k is denoted p_{ij}^k. The strategy describes a set of actions under which the system is run. Here the strategy defines the crop, cultivation, sowing time and herbicide control. 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

$$\lambda = \frac{1+I}{1+\Omega} \quad (2)$$

where I is the current rate of inflation, here assumed to be 3%, and Ω is the interest rate, here assumed to be 6 %, giving λ the value 0.9717.

The solution of Equation 1 consists of a set of decision rules that describe the actions that should be followed given the state at the beginning of year t. Collectively, these rules form a strategy (usually known as policy in dynamic programming literature) 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 infinite horizon solution 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. For reasons discussed later, the model described here is solved as a finite horizon problem.

Defining the state variable

To use a stochastic dynamic programme, the state variable (the weed seedbank density in each layer, seeds m^{-2}) needs to be composed of discrete states. This is achieved by dividing the seedbank density into ranges. Sells (1993) divided the seedbank density into bands that increase in a geometrical progression, because of the exponential nature of weed population growth. A similar approach is taken in Weed Manager, but the bands used are related to the plant density bands used elsewhere in the system. As the relationships are dependent on the transition probabilities, and are also used when setting the initial states, the details will be described in a later section. For each layer there are six bands:

$[L_l(i-1), L_l(i))$, $i = 1,...,6$; $l = s$ (shallow) or d (deep)

For a single weed species in the dynamic programme, the state of the system is thus described by a pair of index values (i_s , i_d), where i_s is the shallow seedbank index and i_d is the deep seedbank index. If n weed species are considered at the same time, the state of the system is therefore described by $2n$ index values. Each combination of these index values is

a single state in the dynamic programming formulation, so the total number of states increases exponentially with the number of weeds.

The seedbank dynamic model

The seedbank dynamic model describes the effect of a strategy on the weed seedbank. The starting point of the annual life cycle is taken, for convenience, shortly after the harvest of the crop. At this time, the entire weed population of each species is present only as a seedbank. The numbers of seeds (seeds m^{-2}) in the shallow and deep layers at the start of year t are denoted by $N_s(t)$ and $N_d(t)$ respectively. The shallow layer is defined as the top 5 cm and the deep layer as between 5 and 25cm, the latter being the average depth of ploughing in the UK.

When soil is then cultivated, a proportion d of the seeds in the shallow layer are buried to the deep layer and a proportion u of the seeds in the deep layer are brought up to the shallow layer. A proportion g of the seeds in the shallow layer then germinate (seedling establishment is possible only from seeds in the shallow layer). Herbicides are then applied with a proportion $1-\theta$ of the seedlings surviving to become mature plants. The number of mature plants in year t is therefore

$$N_m(t) = [N_s(t)(1-d) + N_d(t)u]g(1-\theta) \qquad (3)$$

The number of viable seeds produced by the mature plants is

$$S(t) = \frac{N_m(t)(1-l)vh\beta}{1+\alpha N_m(t)} \qquad (4)$$

where α and β are constants relating plant density to fruit production, v is the proportion of seeds that are viable, l is the proportion of seeds lost by herbivory and h is the number of seeds per fruit (note, *h for some weed species* is 1).

If m is the proportion of ungerminated seeds that die in the soil per year. Then the number of viable seeds that persist in the shallow layer during year t is

$$Q(t) = [N_s(t)(1-d) + N_d(t)u](1-g)(1-m) \qquad (5)$$

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

$$N_s(t+1) = S(t) + Q(t) \qquad (6)$$

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

$$N_d(t+1) = [N_s(t)d + N_d(t)(1-u)](1-m) \qquad (7)$$

Season of drilling

The rotational model augments the kill of seedlings, θ, from mechanical and herbicide weed control measures, with the loss of weed seedlings due to delayed drilling. This is done by using the seasonal emergence patterns of the weed species Mortimer (1990), that were described by a cubic polynomial relation between accumulative seedling emergence and day of the year (Benjamin *et al.*, 2005) . The proportion of kill due to delayed drilling was assumed to be the ratio number of seedlings that emerged before drilling to the total number of seedlings to emerge.

An earliest possible seedbed preparation date was defined for each crop, based on expert opinion. The period of total seedling emergence was assumed to be from this earliest sowing date to 60 days after this date, or, for spring-sown crops, from the 1st August of the previous year to 60 days after the earliest sown date. The period for emergence for seedlings that emerge before drilling is from the earliest sowing date to the date of drilling, or, for spring-sown crops, from the 1st August of the previous year to the date of drilling.

The amount of emergence on each day was calculated by differentiating the cubic polynomial equation in Benjamin *et al.* (2005). This value was not allowed to be negative, which can occur with cubic polynomials. The more simple approach of differencing the values of emergence at two dates from the undifferentiated cubic polynomial was not taken because the slopes of the curve could be negative.

Calculating the transition probabilities
The stochastic dynamic programme requires the probabilities associated with going from a known state i in year t to each of the possible states in year $t + 1$ for a defined strategy. Ideally each of the model parameter values should be described by a probability distribution, as this reflects the natural processes occurring. However, it is not always practical to assign a distribution to each of the parameters, either because of lack of appropriate data or because the calculations are computationally too time consuming. Sells (1993) considered only the effect of the herbicide application to be uncertain in her models as this had the largest effect on future seedbank. She considered the effects of five commercial herbicides for which she had data, but because of the way herbicide effects are included here, no similar data are available for Weed Manager (see section on 'The strategy' below). For simplicity, the uncertainty in seed numbers is solely attributed to the uncertainty of the starting state.

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 year $t + 1$ for a given strategy are calculated. To do this, equations 3–6 are used. 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 $N_d(t) = L_d(i_d - 1)$ are substituted in these equations. Similarly, the highest shallow seedbank density in season $t + 1$ (ρ_H) is given when $N_s(t) = L_s(i_s)$ and $N_d(t) = L_d(i_d)$ are substituted in equations 3–6. Further, it is assumed that having started in initial state $[i_s, i_d]$ the shallow seedbank density in year $t + 1$ 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 year $t + 1$ is therefore given by the proportion of range (ρ_L, ρ_H) that overlaps the range defined by state j_s. That is

$$P_{[i_s, i_d], j_s} = \frac{\left\| (\rho_L, \rho_H) \cap (L(j_s - 1), L(j_s)) \right\|}{\left\| (\rho_L, \rho_H) \right\|} \qquad (8)$$

where $\| \ \|$ denotes the length of an interval.

A similar calculation is carried out to define the probability of going from state $[i_s, i_d]$ in year t to the deep layer state j_d in year $t + 1$. In this case the possible range of values that can occur in year $t + 1$ is calculated using equation 8.

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. For example, for the two weed case, the probability of weed species A in state $[i_s^A, i_d^A]$ and weed species B in state $[i_s^B, i_d^B]$ going to states $[j_s^A, j_d^A]$ and $[j_s^B, j_d^B]$ the following year is

$$P_{i,j} = P_{[i_s^A, i_d^A], j_s^A} \, P_{[i_s^A, i_d^A], j_d^A} \, P_{[i_s^B, i_d^B], j_s^B} \, P_{[i_s^B, i_d^B], j_d^B} \qquad (9)$$

where state $i = \{[i_s^A, i_d^A], [i_s^B, i_d^B]\}$ and state $j = \{[j_s^A, j_d^A], [j_s^B, j_d^B]\}$.

Seedbank band limits and the initial state

As discussed above, it is necessary to divide the shallow and deep layer seedbanks into discrete bands or ranges. These need to be related to the bands used for plant density elsewhere in the Weed Manager system. Estimating seedbank density is very difficult, so users are asked to assess the expected weed density of each species emerging in the crop during the autumn with the selected cultivations, in the absence of herbicides. This assessment is based on four bands, which were chosen to represent similar yield losses for each species. The seedbank bands in the rotational model refer to the number of seeds after harvesting the previous crop and before autumn cultivations. Relating the two sets of bands and setting the initial seedbank therefore involve the germination rate and the effects of cultivations.

Consider first the relative numbers of seeds in the shallow and deep layers. Solving equation 7 for steady state, gives

$$N_d / N_s = (1 - m)d / (1 - (1 - u)(1 - m)) \qquad (10)$$

In practice, the seedbank is unlikely to be in steady state, but this is an adequate approximation. Now, rearranging equation 3 gives

$$N_m / N_s = (1 - d + uN_d / N_s)g(1 - \theta) \qquad (11)$$

However, θ depends on the timing of germination and the herbicides used. As the initial density is set in the absence of herbicides, their effect can be neglected. By tabulating the values for all weeds and both methods of cultivation, it was found that an adequate approximation could be obtained simply by using

$$N_m / N_s = g / k_c \qquad (12)$$

where k_c is a constant depending on the type of cultivation: 10 for ploughing and 2.5 for non-inversion. Equations 12 and 10 thus provide a simple way of setting the initial seedbank states from the expected number of plants.

To define the band ranges, first consider the 4 bands used for the assessment of expected plant density

$[L_p(i-1), L_p(i)), i = 1,...,4$

where $L_p(0) = 0$ for all weed species. These are converted to an approximate geometric progression as follows:

$$L_q(0) = L_p(0)$$
$$L_q(1) = L_p(1) / 4$$
$$L_q(2) = L_p(1)$$
$$L_q(i) = L_q(i\text{-}1)\ r, \text{ for } i = 3,...6$$
$$\text{where } r = (L_p(3)/L_p(1))^{1/3}.$$

This replaces the upper 3 bands of the plant density with a geometric progression of 4 bands. The lowest band is split into 2, where the ratio of the split is the ratio between the k_c values for ploughing and non-inversion cultivations. The shallow band limits are then

$$L_s(i) = L_q(i)k_c / g \qquad (13)$$

with the corresponding deep band limits defined by equation 10. The choice of limits for bands 1 and 2 is such that the lowest plant density band maps to band 1 when using non-inversion tillage and band 2 when ploughing.

These band definitions were tested by running the model for all weed species and all bands, with no herbicide, to ensure that the predicted number of plants in the first year was approximately the same as that set in the initial conditions.

Calculating the yield loss due to weed density
The financial benefit associated with going from state i in year t to state j in year $t + 1$ for a given weed control strategy k is

$$R_{ij}^k = [Y_0 - Y(t)]\ m_c - v_c - c_c - h_c \qquad (14)$$

where k indicates the chosen strategy (which defines crop, sowing time, cultivation, and herbicide control), Y_0 is the expected weed-free yield of the crop, $Y(t)$ is the yield loss from the weeds, m_c is the crop market value, v_c are the variable costs associated with growing the crop, c_c is the cost of the chosen cultivation sequence and h_c is the herbicide programme cost.

The yield loss from several weeds is assumed to be the sum of the losses from the individual species. The yield loss from a single species has to be calculated from the state variables. Re-arranging equation 6 gives the number of seeds that were produced

$$S(t) = \max\left(N_s(t+1) - Q(t), 0\right) \qquad (15)$$

The value of $S(t)$ 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. As it is possible to get negative values of $S(t)$ it is necessary to include the "max" term.

Rearranging equation 4 gives

$$N_m(t) = \frac{S(t)}{(1-l)vh\beta - S(t)\alpha} \qquad (16)$$

Then substituting in the value calculated for $S(t)$ in equation 15 gives the number of mature plants ($N_m(t)$). The yield loss due to the presence of the weed is

$$Y(t) = \frac{Y_0 r N_m(t)}{1 + \gamma N_m(t)} \qquad (17)$$

where Y_0 is the expected yield in a weed free crop and, r and γ are constants. This follows the density dependent hyperbolic model of Cousens (1985).

The strategy

The strategy identifies the set of actions under which the model is run. In our case the strategy defines the crop, cultivation, sowing time and herbicide control. In the model described here the choice of crop will affect the estimate of the weed free yield Y_0, the crop market value m_c, and the variable costs v_c in equation (14). The crops considered are winter and spring wheat (*Triticum aestivum* L.), winter and spring barley (*Hordeum vulgare* L.), winter and spring oilseed rape (*Brassica napus ssp oleifera* (DC) Metzg.), winter and spring beans (*Vicia faba* L.), spring peas (*Pisum sativum* L.), potatoes (*Solanum tuberosum* L.), sugarbeet (*Beta vulgaris* L.) and a ryegrass ley (*Lolium spp.*).

Cultivations affect the migration of seeds between shallow and deep layer. Therefore the parameters d and u in equations 3, 5 and 7 are cultivation dependent. For simplicity, instead of modelling each individual cultivation of a seedbed preparation, three classes of cultivation sequence are considered. These are defined as inversion, non-inversion or rotary cultivation. Some cultivation sequences are not permitted in some crops. In a potato crop only rotary cultivation can be used. Inversion or non-inversion cultivation can be used in all other crops.

Sowing time affects both the expected weed free crop yield Y_0 (equation 14) and the proportion of weed seedlings that can be killed by cultivations during seedbed preparation. Hence, although later sown crops have a reduced expected yield, delaying sowing improves weed control.

The amount of control achieved by herbicides is described by parameter θ in equation 3. Within Weed Manager, 12 weeds growing in 12 crops are parameterised. Parameterising θ for all currently available commercial herbicides is not feasible. 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 a weed given the costing band of the herbicide programme. The philosophy being that cheap programmes will effectively control weeds which are easy to kill in a crop, whereas, a more expensive programme is needed to kill harder to manage weeds, such as winter emerging weeds in an early autumn-sown crop. There may be occasions where a weed that is difficult to control can be controlled cheaply, but these will be the exception rather than the rule.

Solving the dynamic programme

Backward recursion solution iteration (Howard, 1960) was used to solve the dynamic programme, to determine the most cost-effective combination of crops, cultivations and weed control practices. In this method, a starting solution f_F is chosen that represents the final year's reward. Equation 1 is then solved iteratively until either the solution reaches a steady state or a maximum number of iterations have been completed. It was decided that

the dynamic programme with two weeds should be solved on a 2.8GHz personnel computer in less than a minute. The maximum number of iterations (years) achievable in this time was 10. It was unlikely that the system would have always reached steady state in this time so the estimate of f_F suggested by Sells (1995) was used:

$$f_F(j) = \frac{R_{jj}}{1-\alpha} \quad (18)$$

where R_{jj} is the reward associated with going from state j to state j under an arbitrarily chosen strategy, and α is the discount factor calculated in equation 2.

The time required to solve a dynamic programme is proportional to the square of the number of states. In this problem, there are 36 states for each weed, so the time increases by a factor of 1296 for each weed added. Test runs confirmed this: took about 14 s to solve the dynamic programme for two weeds, and 15540 s for three. The latter is an unacceptable time to wait for a solution, so when the weed list contains more than two weeds, only the two most competitive species are considered. If there are two species of equal competitively, then the one with the higher initial density banding takes precedence. This implementation does not guarantee that the optimal solution is found but does produce a solution that is practically sound.

Results and discussion
Performance of the model
The population dynamics of three weed species (*A. myosuroides, Anisantha sterilis* (L.) Nevski and *Stellaria media* (l.) Vill.) was simulated using the Moss (1990) model over a five year rotation, with contrasting combinations of cultivations, drilling dates and herbicide efficacies (Table 1). The three weed species represented a range of population dynamics parameter values (Table 2). For example, *A. myosuroides* is characterised by moderate seedbank persistence, viability and germinability; *A. sterilis* has no persistence in the soil seedbank, but high viability and germinability and *S. media* is characterised by long seedbank persistence, moderate germinability and high viability (Table 2).

For *A. myosuroides*, rotation 1, which had a continuous tine (minimal soil cultivation) on a mid date drilling (14 October), led to a steady increase in population size, despite a 90% kill annually from herbicides (Table 3). A plough in year 3 of this rotation reduced the population 19 fold in rotation 2 compared with rotation 1. Imposing ploughing in years 3 and 4, however, produced a density of *A. myosuroides* in year 4 as great as that from continuous tine, comparing rotations 1 and 3. Ploughing continuously from years 2 to 5 caused a 146 fold reduction in plant density in year five compared with continuous tine (rotation 4 compared with rotation 1). Interestingly, in rotation 4, there was an increase in plant density from years 2 to 3, presumably because ploughing for the second time had brought viable seeds back up to the surface.

Tine cultivations combined with drilling early (1st August) in years 2, 3 and 4, caused a 2.1 fold increase in plant density in year 4 compared with a continuous mid drilling date in each

year (comparing rotations 5 and 1). This effect of drilling date was because of the reduced kill of weeds in the early drilling. Correspondingly, drilling late (1 December) in years 2, 3 and 4, caused a 2.2 fold decrease in plant density in year 4 compared with a continuous mid drilling date in each year (comparing rotations 6 and 1).

Combining ploughing with early season drilling resulted in a reduction in plant populations compared with continuous tine cultivations (rotations 7 compared with 1), but the reduction was not as great as when compared with ploughing in mid date drilling (rotations 7 compared with 4). Similarly, combining ploughing with late season drilling resulted in a marked reduction in plant populations compared with continuous tine cultivations (rotations 8 compared with 1), and the reduction was greater than ploughing in mid date drilling (rotations 8 compared with 4).

Ploughing was particularly effective in reducing populations. For example, in rotation 9, the population was allowed to increase to 126 plants m^{-2} in year 2 by tine cultivations combined with an early drilling (Table 3), but a plough in year 3 brought about a 10.7 fold decrease in density from years 2 to 3 in rotation 9. In contrast, late tine cultivation in year 3 instead of a plough in year 3 did not even cause a reduction in plant density from years 2 to 3 in rotation 10. Interestingly, ploughing in year 3 in rotation 9 gave a better weed control in year 3 than increasing the effectiveness of the herbicide from a 90 to 99 percent kill (comparing rotations 11 and 9).

The pattern of results for *A. sterilis* were broadly similar to those observed for *A. myosuroides,* but the populations of *A. sterilis* were more responsive to control measures (or lack of them) than *A. myosuroides.*

The results of running the dynamic programme
Running the dynamic programme for any two weeds always gave the optimal strategy of growing continuous potatoes. This is because when considering only crop value and variable costs potatoes are a very profitable. In actual fact, to grow potatoes a farmer must have invested substantially in suitable equipment and so fixed costs (which are not included) make it a less attractive crop. Additionally there are disadvantages to continuous cropping that are not included in the model, such as a reduction in appropriate nutrients and increased risk of disease from season to season; both causing yield reduction. This meant that allowing to dynamic programme to choose the crop, leads to unsatisfactory results. Therefore a fixed rotation was imposed on the dynamic programme. This rotation is selected by the user and can be between two and five seasons in length. The dynamic programme is then left to decide sowing time, cultivation, and herbicide control. This effectively means the state is now described by the season within the rotation as well as the seedbank density. If there are *n* seasons in a rotation then the probability of going from a state in season *i* to one other than in season *i+1* is zero, unless *i* is the nth state in which case the only non-zero probabilities are associated with going to states in season 1.

Comparisons with other decision support systems

The wheat disease manager is an arable crop decision support system worthy of note. A mechanistic model is used to simulate the effects of fungicide programmes on winter wheat disease induced yield loss (Milne *et al.,* 2004, Audsley *et al.* 2005, Milne *et al.* 2006). The model was designed to couple with a genetic algorithm optimisation routine (Parsons & TeBeest, 2003) which produces a list of good fungicide programmes for a user specified scenario. Unlike weed control there is little to be gained from taking a long term (i.e. multiple season) view of disease control so the system simple considers a single season at a time.

The model described here is stochastic which means uncertainty can be incorporated in a meanful way at each point of the simulation. Unfortunately current computational hardware is not sufficiently powerful to incorporate uncertainty at all appropriate points in the simulation, and in fact in many cases sufficient data does not exist to parameterise the uncertainty. None the less even with the limited amount of uncertainty incorporated into the model described here the resulting variability means that solutions will be more robust.

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Table 1 Contrasting rotations and cultural practices applied to models for *A. myosuroides, A. sterilis* and *S. media* Cultivations: tine cultivation or ploughing. Drilling dates early = 1 August, mid = 14 October, late = 1 December). For Tine cultivations $d=0$ and $u=0$, for plough cultivations $d=0.95$ and $u=0.35$, Herbicides kill 90 percent of weeds in each year, except in year 3 of rotation 11, where the herbicide kill is 99 percent.

Rotation number	Year				
	1	2	3	4	5
1	Tine, mid	Tine, mid	Tine, mid	Tine, mid	Tine, mid
2	Tine, mid	Tine, mid	Plough, mid	Tine, mid	Tine, mid
3	Tine, mid	Tine, mid	Plough, mid	Plough, mid	Tine, mid
4	Tine, mid	Plough, mid	Plough, mid	Plough, mid	Plough, mid
5	Tine, mid	Tine, early	Tine, early	Tine, early	Tine, mid
6	Tine, mid	Tine, late	Tine, late	Tine, late	Tine, mid
7	Tine, mid	Plough, early	Plough, early	Plough, early	Plough, mid
8	Tine, mid	Plough, late	Plough, late	Plough, late	Plough, mid
9	Tine, mid	Tine, early	Plough, mid	Tine, early	Tine, mid
10	Tine, mid	Tine, early	Tine, late	Tine, late	Tine, mid
11	Tine, mid	Tine, early	Tine, early	Tine, early	Tine mid

Table 2. Parameter values of the Moss (1990) model used in evaluating different rotations for *A. myosuroides, A. sterilis* and *S. media*

Parameter	*A. myosuroides*	*A. sterilis*	*S. media*
α	0.0018[1]	0.002[3]	0.008[4]
β	3.88[1]	120[3]	840[4]
g	0.30[2]	0.60[3]	0.27[5]
h	100[1]	1.0[8]	1.0[8]
l	0.55[1]	0.58[3]	0.78[5]
m	0.7[1]	1.0[3]	0.3[7]
v	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

[8] Plants assumed produce one seed per head or capsule

Table 3 The number of mature *A. myosuroides* plants (m^{-2}) surviving each year under the rotations described in Table 1

Rotation number	Year				
	1	2	3	4	5
1	42.4	89.0	174.7	307.0	466.6
2	42.4	89.0	9.1	20.1	43.6
3	42.4	89.0	9.1	18.5	40.3
4	42.4	5.6	9.7	4.1	3.2
5	42.4	126.1	322.8	656.5	709.2
6	42.4	63.6	96.4	139.7	268.1
7	42.4	7.9	14.1	7.0	4.4
8	42.4	4.0	6.8	2.5	2.4
9	42.4	126.1	11.7	36.6	75.2
10	42.4	126.1	162.9	217.4	381.6
11	42.4	126.1	32.3	155.6	270.3

Table 4 The number of mature *A. sterilis* plants (m^{-2}) surviving each year under the rotations described in Table 1

Rotation number	Year				
	1	2	3	4	5
1	87.2	292.8	728.3	1169.4	1381.5
2	87.2	292.8	36.4	133.9	416.5
3	87.2	292.8	36.4	6.7	26.1
4	87.2	14.6	2.8	0.6	0.1
5	87.2	497.7	1672.7	2581.4	1652.2
6	87.2	166.1	279.1	400.9	877.6
7	87.2	24.9	7.9	2.6	0.5
8	87.2	8.3	0.9	0.1	0.0
9	87.2	497.7	49.2	300.3	740.1
10	87.2	497.7	558.3	590.3	1067.8
11	87.2	497.7	167.3	840.5	1236.6

Table 5 The number of mature *S. media* plants (m^{-2}) surviving each year under the rotations described in Table 1

Rotation number	Year				
	1	2	3	4	5
1	33.2	43.8	51.0	55.5	58.4
2	33.2	43.8	3.9	10.9	22.8
3	33.2	43.8	3.9	12.9	25.4
4	33.2	4.2	11.6	8.8	9.8
5	33.2	70.2	86.0	95.4	62.9
6	33.2	37.1	42.3	45.7	56.3
7	33.2	6.7	18.8	15.8	11.6
8	33.2	3.6	9.8	7.1	9.3
9	33.2	70.2	4.1	17.9	27.5
10	33.2	70.2	45.5	47.7	57.8
11	33.2	70.2	8.6	67.7	52.6

A model based algorithm for selecting weed control strategies that maximise profit margin in winter wheat

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Abstract

To be completed

Introduction

Weed control in UK arable crops is an expensive necessity for all arable farmers. It is generally achieved using a combination of cultivations and herbicides: the aim being to maximise profit margin. The choice of cultivations and herbicides is not straight forward. It depends on what weeds are growing in the field, and how damaging their presence is to the crop. There is little point controlling a weed if the cost of the control exceeds the income gained from removing it. Cultivations can both stimulate weeds to grow and act as a hoe. One common practice is to cultivate well before sowing hence stimulating weed growth, then follow this with a herbicide or cultivation prior to sowing to kill the weeds that have emerged. This removes a proportion of the weeds that would have otherwise come up in the crop. The ability of an herbicide to control a weed will depend on product, application timing and dose, as the sensitivity of a weed to a product will depend on the amount of chemical applied and the growth stage of the weed. Typically *n* herbicide applications are carried out within a season, each potentially comprising of a mixture of products.

The decision algorithm presented here aims to provide a list of alternative weed control strategies that maximise profit margin over weed control costs in a winter wheat crop. The algorithm interfaces with a model of weed and crop growth which estimates yield loss due to weeds for a given control strategy. The weed model is parameterised for weed species black-grass, chickweed, cleavers, wild oat, barren brome, Italian ryegrass, annual meadow grass, fat hen, poppy, knotgrass, volunteer winter oilseed rape and volunteer field beans. The model and decision algorithm were developed for use in a decision support system that would be run on a home PC (Collings *et al.*, 2003). The decision support system was designed so that the user selects a subset of weeds that they are interested in controlling in their field. They can then either choose to run the models with their own control strategies or ask the system to suggest a list of alternative control strategies. These are calculated by the decision algorithm described here.

Many algorithms have been developed to optimise systems. Objective function… form of model and data made it difficult to use these … speed of system search space discrete *Algorithm designed around model and data…………..to complete*

The aim of the optimiso be used in a home PC decision support system it is important that the optimisation algorithm runs quickly (ideally in less than a minute). There are many methods of optimising systems such as ….() but these rely on the a continuous whasit surface. The form of the herbicide data and model mean that there will be discrete jumps in the surface making these algorithms in appropriate. On top of this optimisation algorithms will run the model thousands of times and so a really fast run time is important.

The search space is large so the algorithm needs to know the yield loss associated with applying potentially thousands of different herbicide and cultivation programmes. This is not practical as the time taken would be too great. Therefore efficient ways of searching and filtering solutions were devised. These were based on expert knowledge of weed control, the form of the model, and herbicide and cultivation data.

Method

The weed and crop models
The model simulates the emergence and growth of grass and broad-leaved weeds in a winter wheat crop, and from this yield loss due to weed infestation is calculated. It is assumed that there is no competition between weed species, which is a reasonable assumption for most commercial conditions. The weed and crop models are reported in Benjamin *et al.* (2005), here we outline the features relevant to the optimisation algorithm.

To initialise the weed and crop models an estimate of the expected number that will emerge is required. The user is asked to provide this information by selecting from one of 4 categories. For winter wheat the categories are   ….. , for the weed the ranges are weed dependant but they represent the numbers of weeds which would cause between $0 - 10\%$, … yield loss in an untreated crop.

The emergence and growth of the winter wheat crop is simulated as a single cohort of seedling emergence, with the density of plants (plants m^{-2}) taken as the average of the user specified range. It is not reasonable to model each weed species as a single cohort of seedling emergence as they will typically emerge over a longer period of time than the winter wheat crop, the extent of which will depend on – amongst other factors – the particular species. Therefore each weed species is simulated as eight cohorts. The total density of plants of a weed is the average of the user specified range, and this is assumed to be equally distributed between the cohorts. Cultivations can stimulate the emergence of weed seedlings and therefore the emergence pattern of the weed cohorts depends on the seedbed preparation. If the seedbed preparation consists of only direct drill, one of the weed cohorts germinates on the drilling date (we refer to this as cohort 1) and the others (cohorts 2 – 8) germinate at specified intervals from the date of the last crop's harvest. These intervals depend on weed species, cohort number, temperature and soil water content. Note that cohorts 2 – 8 germinate in numerical order, but cohort 1 may germinating out of this sequence (depending on the timing of drilling) often it occurs between cohorts 2 and 8. If the seedbed is prepared by a sequence of cultivations that does not include ploughing, then the calculation of cohort emergence is identical to the direct drill case except that the germination of the final cohort (cohort 8) is brought forward to the date of the first cultivation. The biological justification for this is that the delay in emergence of the final cohort is due to a dormancy mechanism which is broken by soil disturbance. If the seedbed preparation includes ploughing, the timing for germination of cohorts 2 – 8 is calculated from ploughing instead of the previous crop harvest date. Cohort 1 still germinates on the

drilling date. The biological justification for this is that ploughing inverts the soil profile burying and destroying those seedlings that have emerged, seeds that have germinated and those that would have germinated. The model assumes that the seeds being brought to the surface will be of similar number to those being buried to a depth where they cannot germinate.

The weed and crop grow as a function of daily weather variables with growth stage and GAI being calculated. The progress of development for crop and grass weeds is measured by the Zadoks scale (Zadoks *et al.* 1974). The development of the broad-leaved weeds is measured in terms of the number of leaves on the plant. The simulation of green area index (GAI) continues until the sum of the individual GAI exceeds 0.75. This point in time is defined as canopy closure. The ratio of the GAI of an individual weed species to the GAI of the crop is used to estimate the crop yield loss due to that species. The total yield loss due to weed infestation is the sum of the yield loss of each individual species.

Herbicides and cultivations
The effect of using herbicides on yield loss is modelled by reducing the GAI of each of the weed cohorts at canopy closure. The size of the reduction depends on the product used, weed cohort growth stage (or timing) and dose. This information is captured in the herbicide data.

The herbicide efficacy data in the system is extensive with information on the activity of over *n* herbicides against each of the weed species modelled, including all resistant types. The data takes a similar form to product label data, with efficacies given for fixed doses against weed species at consecutive growth stage ranges. For grass weeds the growth stage ranges are $0 - 7, 8 - 10, 11 - 13, 14 - 21, 22 - 29, 30 - 31, 32 - 39, 40 - 45$ and $46 - 93$; for broad-leaved weeds the ranges are pre-emergence, pre-emergence – cotyledons, cotyledons – two leaves, two – four leaves, four – six leaves, six – eight leaves, and eight leaves – flowering. The efficacies are categorised as resistant (R), moderately resistant (MR), moderately sensitive (MS), sensitive (S) and complete kill (G). These map to 1.0, 51.0, 76.0, 91.0 and 100.0 percent kill in the model.

Mixtures and sequences of products are dealt with in one of two ways. If a product mixture (including product plus adjuvant) is known to be synergistic then the combination is treated as a pseudo product with its own efficacy data. Otherwise the combined efficacy *E*, of products either in mixture, sequence or both is calculated by:

$$E = \prod_{i=1}^{n} (1 - e_i) \qquad\qquad (1)$$

where e_i is the efficacy of the ith product (or pseudo product) against the weed at the cohort growth stage at which it was applied, and *n* is the number of products in the herbicide programme.

Rules on timing and dose of herbicides need to be incorporated into the decision algorithm in order for it to produce sensible results. In the system these rules belong to one of two categories. The first are restrictions data (or approvals data), which are part of the legal registration process, therefore mandatory and every chemical has them. The second are recommendations for effective use, and are defined by the herbicide companies. They often partially duplicate the approval and most are on the product label. The restrictions data includes rules on maximum dose for a single application, maximum total dose, and restrictions on the timing of application. The rules on timing can be in terms of crop growth stage, calendar date, or a restriction on application within a fixed number of

days from an event such as drilling or harvest. The recommendations data also include advice on timing of application. These recommendations are also in terms of either crop growth stage, within/not within a fixed number of days of an event or calendar date. For example if a product is known to perform badly in cold weather there will be a recommendation not to apply over the winter period (which is defined in terms of date). Both the restrictions and recommendations data contain "do not mix" rules. In the case of the restrictions data these rules prohibit dangerous tank mixes, where as the recommendations data prohibits the mixture of products that are known to be antagonistic or the effects of mixing are unknown.

As well as affecting the emergence patterns of the weed cohorts, cultivations also act as weed control measures. They are processed in the same way as herbicides, each cultivation having efficacy data and timing restrictions in the forms described above. There are also restrictions on the sequences of cultivations that can be used pre-sowing. These restrictions ensure that the sequence of cultivations prepare the seed bed sufficiently for sowing (ref?).

The optimisation algorithm – sowing date is fixed and drills have no kill
The optimisation algorithm's objective function is the margin over weed control costs which is given by

$$M = (Y - Y_L)g - H - C \tag{2}$$

where Y is the expected yield in a weed free winter wheat crop, Y_L is the model estimate of yield loss due to weed infestation, H is the cost of the herbicide programme and C is the cost of the cultivation programme.

Running the model once takes over a second on a ** PC which if run thousands of times in the algorithm, would make the time taken to obtain a set of solutions unacceptable. One of the slowest parts of the model is calculating the emergence pattern of the weeds, which depends on the pre–sowing cultivation programme. The next step in the model is to grow the weeds and crop to canopy closure and to evaluate the GAI of each weed cohort and the crop at canopy closure (this step is also time consuming). After this herbicide and post sowing cultivation effects are imposed and yield loss calculated. Once the emergence pattern is evaluated, herbicides and post–sowing cultivations have no effect on the model growth stage estimates or the GAI at canopy closure. The algorithm was designed to take advantage of this model feature by running the slower parts of the model a minimum number of times. Firstly a maximum of three pre-sowing cultivation programmes are defined. The model is run to canopy closure with the first of these, and the GAIs are stored. A list of viable herbicide and post-sowing cultivations are defined and their effects on the weed GAI are calculated using Equation 1. These were applied in turn to the canopy closure GAI and the revised GAIs are used to calculate the yield loss due to weed infestation using the same relationships that are used in the model (Benjamin *et al.*, 2005). The margin is calculated using Equation 2 and stored with the complete herbicide and cultivation programme. This procedure is carried out for each of the cultivation programmes. Finally the weed control programmes are sorted in terms of margin and up to the top 20 are displayed to the user. A schematic of the process is shown in Figure 1.

Defining the pre-sowing cultivation programme The system has efficacy data and restrictions information on 14 cultivations. These are mouldboard plough, spring tine, harrows, rollers, powered harrows, rotary cultivator, heavy tines, discs, heavy disc, drill direct, drill, tine weeding, and inter-row hoeing. The first 9 are can only be applied before sowing, the next two on the drilling date and the last two can only be applied between sowing and crop growth stage 31. There are many possible pre-sowing cultivation sequences that could be considered. The model structure means that even searching though a few of

these will take a very long time. Because of this we only consider a subset of cultivation plans.

If the current date is before the sowing date and no cultivations have applied previously in that season then up to three pre-sowing cultivation plans will be defined. The first is made up of the sequence cultivation 1 on the day after the current date, cultivation 2 on the day before the sowing day and a drill on the sowing day. The reason for this structure is that the first cultivation will stimulate weeds to grow, and then the second will remove a proportion of those that have emerged before sowing. To maximise the number of weeds that will have emerged the maximum amount of time is left between the first two cultivations. This sequence is tested for all combinations of cultivations 1 and 2, including those where cultivation 2 is null. The sequences are tested to ensure that they do not fail any restrictions. The model is then run with those that pass, and the margin calculated. The cultivation plan which gives the highest margin is defined as the first pre-sowing cultivation programme. The second cultivation programme is mouldboard plough two days before sowing, harrow the following day and finally and drill. This is included because ploughing inverts the seed bed and so weeds coming up in the crop will have been stimulated at this point in time, not before. This makes them less competitive with the crop. The third cultivation programme is simply direct drill.

If the current date is before the sowing date and a cultivation (or cultivations) has already been applied then only one cultivation sequence is considered. This is made up of the cultivations that have been applied in the past, cultivation 1 on the day before sowing, and drill on the sowing date. This sequence is tested against the restrictions with cultivation 1 being any one of the possible cultivations including null. The model is then run with those that pass, and the margin calculated. The sequence that gives the highest margin is chosen to be the cultivation.

If no cultivations have been applied and the current date is within two days of sowing the cultivation sequence is direct drill.

Comment on the fact that the way of choosing cultivations doesn't guarantee the optimal result but does insure that sub optimal solutions are found. Define valid

Defining the herbicide and post-sowing cultivation programme Within the context of the model the cultivations considered here act in the same way as herbicides so for simplicity we will refer to herbicides and cultivations as products. The season is split into four concurrent spraying periods, namely pre-emergence, autumn, spring and desiccant. Pre-emergence is defined … In each period a maximum of one product or product mixture can be applied by the algorithm. This follows the usual practice of farmers where a spray in each period would be targeted at species (or in some cases cohorts) that emerge at different times of the year. To search all possible combinations of product sequences would take to long so we needed to reduce the search space. This was done by creating a list of valid products and product mixes with an associated application timing for each application window. Valid combinations of products from each window then make up the weed control programmes that are evaluated.

For each application window a set of test timings are defined. These timings are a maximum of 14 days apart (*why 14 days*). Each herbicide and cultivation is then considered in turn. For each defined time the product is tested against the timing and dose restrictions data, if it is valid then the yield loss associated with its application is calculated. The timing which

gives least yield loss for the product is saved with the product in a list. Following this, mixtures of two products are evaluated in the same way and added to the list. Finally a null herbicide is added to the list. Separate lists are created for each application window. Each list is then reduced by removing products which have less than or equal efficacy against the weeds in the weed list than cheaper products in the list. All valid combinations of the reduced lists make up the list of herbicide programmes that are evaluated. This is illustrated in Figure 2.

Filtering the solutions –to complete

Conclusions

To complete

References

Benjamin LR, Lutman PJ, Cussans J, Storkey J (2005) **A model to simulate the growth, development and competitive effect of weeds in a winter wheat crop in the United Kingdom,** *to be submitted*

Figure 1.

Figure 2

```
┌─────────────────────────────────────────────────────┐
│     Split the season into 4 spray application windows │
└─────────────────────────────────────────────────────┘
                          │
                    ┌──────────┐
                    │  i = 1   │
                    └──────────┘
                          │
                    ◇ is i < 5 ◇ ──no──→ ( 4 lists complete )
                          │
                         yes
                          │
┌─────────────────────────────────────────────────────┐
│  Define n test spray timings within application window i │
└─────────────────────────────────────────────────────┘
                          │
                    ┌──────────┐
                    │  p = 1   │
                    └──────────┘
                          │
              ◇ is p < the number of ◇ ──no──→
                          │
                         yes
                          │
                    ┌──────────┐
                    │  j = 1   │
                    └──────────┘
                          │
                  ◇ is j < n + 1 ◇ ──no──→
                          │
                         yes
                          │
             ◇ Does product p pass timing ◇ ──no──→
                          │
                         yes
                          │
┌─────────────────────────────────────────────────────┐
│  Calculate yield loss y associated with applying product │
│                  p at time j                             │
└─────────────────────────────────────────────────────┘
                          │
┌─────────────────────────────────────────────────────┐
│       if y < Y then Y = y and t = j                    │
└─────────────────────────────────────────────────────┘
                          │
                    ┌──────────┐
                    │ j = j + 1│
                    └──────────┘
                          │
┌─────────────────────────────────────────────────────┐
│  if y < 1000 add product p at timing t to the list      │
└─────────────────────────────────────────────────────┘
                          │
                    ┌──────────┐
                    │  p = p+  │
                    └──────────┘
                          │
                    ┌──────────┐
                    │ i = i+ 1 │
                    └──────────┘
```
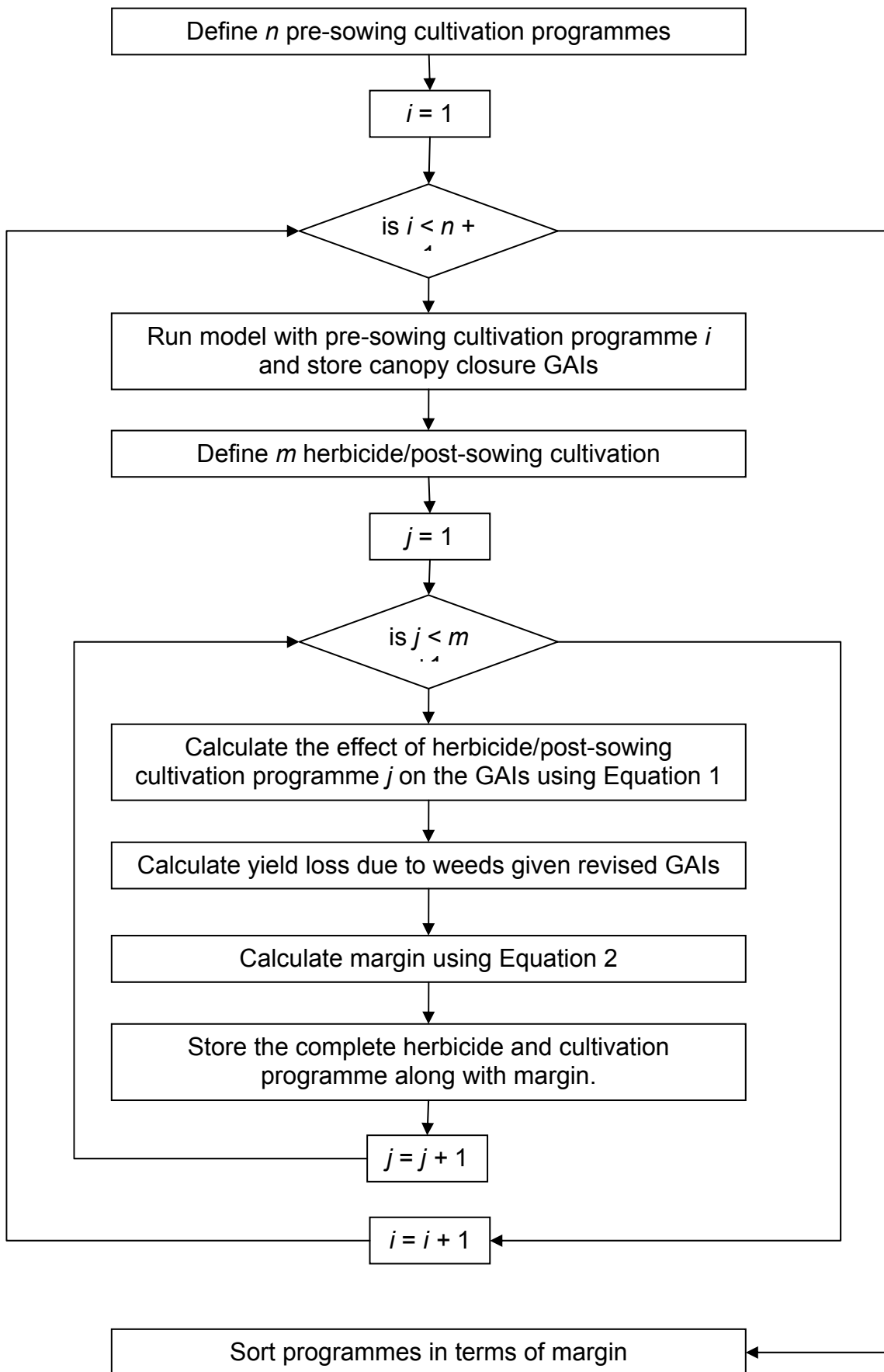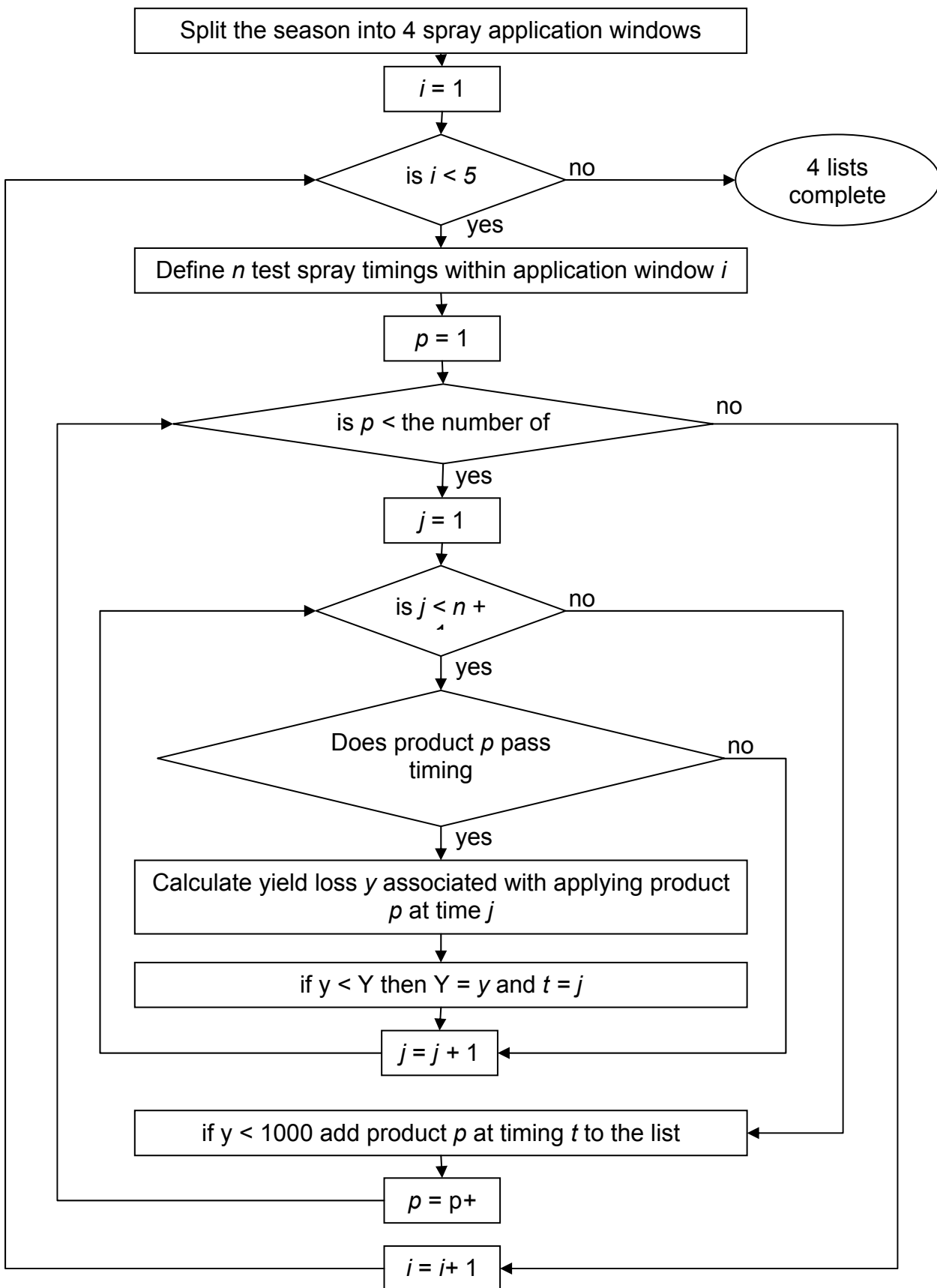
106

System Architecture – A Summary
The outline structure of the system is shown in figure 1 of the main report. All the data is stored in MS Access databases that are accessed via dynamic link libraries. The encyclopaedia is displayed in the Rothamsted browser (Castells-Brooke *et al.*, 1999), which uses the Microsoft Web Browser component to display the encyclopaedia pages. The encyclopaedia is described in detail in (Appendix C). 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 can be developed on multiple sites.

The wrapper
The wrapper component is an OLE in-place and automation server complying with the requirements for decision support modules set out in the final report for 'The framework to enable generation of decision support systems' (MAFF project OCS 9409, 1998). The application was generated using the Microsoft AppWizard and so uses the MFC view of the document/view architecture.

This component provides all the data handling in the document class. This class is used to retrieve the user's data from the ArableDS data sharing environment (DSE). The user's farm and weather data is supplied in databases that are defined by the module and accessed using DLLs as described below. The view class is responsible for displaying the information. In this case, the view has to communicate the information stored in the document to the OCX that is used to implement the user interface and to the spray nozzle selector program.

The view class converts the data into the format required by the OCX component and writes a file containing the necessary spray and cropping information for spray nozzle selector. The in-place frame provides the toolbar used by Weed Manager.

The module weather data is read-only but the farm data is expected to be updated by the module. The user can change several different aspects of the farm data from within the OCX. This requires the view class to respond to an event initiated by the OCX. Changes to the cropping information, farm costs and observations are stored immediately in the local copy of the farm data. The view then passes the data to the document that uses the DLL to write the data to the database. The treatment programs, consisting of cultivations and sprays are stored as a result of user requests not every time the user changes a treatment product or date. This is to allow users to test different scenarios without affecting the underlying data. When the view is notified of a change in a user's plan it sets a flag.

When the user switches to a different module in the DSE or closes the Weed Manager, the user is given the option to save modified plans before all the data is written to the main farm database in the DSE for future use by this or other modules.

The OCX
The user interface and model controlling functionality was developed as an OCX control. The user interface contains two views, figs 3 and 4 , 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 use of an ActiveX control gives several benefits. Firstly, it separates database handling from user interaction. Secondly, it allows the inclusion of the system within a different wrapper program. Any such program would need to provide the same interface functions as the existing wrapper. Finally, it solved some technical difficulties that occur when using multiple views in an in-place server.

Inside the OCX, the data is managed by single class. The data in this class is initially set up by the control class and is then accessed and edited by the two views – within season and rotational – and all the dialogs provided to allow users to enter data. The within season view is designed to provide decision support for weed control in a current crop of currently of winter wheat. This view therefore uses actual herbicide product and cultural control efficacies and prices. The rotational view looks at

the current season and up to five future seasons using expert defined values and published data for calculating the weed control costs and crop values. This part of the system looks at the cultivation, sowing date and control cost options that can be used to control weeds over the set time span. The cultivation and control costs for the current season are transferred from the within season to the rotation screen via the class managing the data.

The user interface interaction with the various models is initiated from many user actions. In order to simplify the development and maintenance processes a class was developed to control the interactions between the user interface and the models and between the models themselves.

One of the user interaction requirements was that the system should provide defaults wherever possible to allow users to interact with the system quickly. Most of the user data is provided by the DSE so is available when the system is first run. Two types of data are not always available in the user data so the module has developed strategies to cope with this. The missing data relates to cultivations or treatments and the identity and type of weeds in the field. The system needs both sets of data in order to function correctly. It was decided to use a standard pre drilling treatment of ploughing followed by harrowing the day before drilling as a default plan. There is no such thing as a standard set and number of weeds in any field so the user needs to enter this before any data can be displayed.

A major function of the system is to allow the user to create cultivation and treatment plans. The user compares plans on the basis of the expected mean outcome and the variability that the system expects around that mean. The user can create an unlimited number of plans in a session. The majority of these plans are only relevant to either the within season or rotational part of the system so the data is held in a specifically defined class and unless specifically requested for storage is deleted at the end of the session.

Users need to be able to print out their plans and requested the ability to print plans without having to save them first. The DSE provides the container for the Weed Manager module. In order to be consistent with Windows standards, the option to print is found under the File menu. This means that the DSE communicates the users request to the wrapper, which then passes the request on to the OCX to allow un-saved plans to be printed.

The spray nozzle selector
The choice of spray nozzle can affect product efficacy and spray drift. In some cases advised spray quality and nozzle type are specified on the product label. Literature also exists, such as the HGCA nozzle selection guide (HGCA, 2002), to help farmers decide which nozzle type to use. The spray nozzle selection support system is a computer application, which draws together label information and expert rules, to evaluate which nozzle type is most appropriate for a given circumstance. Details of the system are available in (Milne *et al.*, 2003).

This program was designed to be applicable to fungicide and insecticide spray programs as well as herbicide programs. It is to be made available to developers of other decision support modules as part of the developers toolkit (DESSAC final report, 2000). The data for the products is held in the DSE pesticide database. The wrapper program provides the spray nozzle sector with information about the current spray plan. The selector program then requests the spray requirement information from the pesticide database and uses the information to suggest suitable spray nozzles and volumes.

The data
In figure 1 in the main report, the data shown above the dotted line is provided by the DSE. The data below the line is part of Weed Manager.

The pesticide data provided by the DSE consists of the statutory information relating to the herbicides that can be used in winter wheat. This information is imported from the LIAISON (www.liaison.csl.gov.uk) database developed by Central Science Laboratory in York. The

information regarding the dose and timing of applications is converted into mathematical terms for use by the decision support process models (Defra final report AR0915). The data from this database are combined with efficacy and tank mix information, provided by the chemical companies, to drive the models used to calculate the expected outcomes and to be viewed by users in the encyclopaedia. In addition, the pesticide database contains default values for the cost of each pesticide and some label data relating to the application of the product.

The basic agronomic data is used to provide default values for drilling and harvest dates, crop value, basic costs for operations such as ploughing, spraying as well as values for the variable costs associated with each crop.

The weather data used in the Weed Manager consists of user data and climate data for the location of the farm(s) (models (Defra final report AR0915). In order to predict the plant growth over the complete season, the system combines the actual user weather data with climate data to provide weather data for the full season.

The user weather data is specific to each site. Weather data can be downloaded from the ArableDS web site with over 100 possible weather sites being available or added from a weather station. Users can also add their forecast data.

The UK is divided into 26 different regions for the provision of climate data, which is intended to provide representative data for the models when forecasting future outcomes. It has been designed in consultation with the developers of several modules. It contains 12-year averages of the daily temperature, solar radiation, and wind and transpiration data. Because rainfall is a sporadic event, and the magnitude of the even is important, daily means are not appropriate, and the method used is designed to ensure that certain rainfall statistics are maintained, including the 5 day mean, the number of dry days and the number of high rainfall days.

The method uses 5-day intervals and calculates the number of dry days and number of days with more than 5mm rain and keeps the numbers correct. The dry days are added consecutively. The data for days with more than 5mm rain is then added. The value used is the total rain in those wet days divided by the number of wet days unless the total of those wet days is more that the average for the full 5 days for all years. In that case it is reduced to 80% of the full value before being assigned to each day. The remaining rain is added to the remaining days to give different proportions on each day.

This calculation is not designed to be a scientifically accurate representation of rainfall patterns but is designed to give reasonable average plant growth and disease predictions for each particular region. The rainfall calculation system gives the average rainfall for 5-day periods and for the whole year so is a reasonable dataset for systems that include soil leaching data. Some diseases are affected by total daily rainfall. The value of 5mm is selected, as this is the amount used to trigger *Septoria tritici* on winter wheat crops. Seed germination requires moist soil. The use of the 5 day average means that the soil does not dry out for long periods and therefore favours weed growth making the prediction risk averse.

The farm specific data consists of farm location, field and cropping information including observations of plant growth and treatment plans. The database also stores the user application, cultivation and herbicide costs and variable crop costs. In order to avoid different decision support modules using different default values for the same items, the DSE provides default values for all data items that are required for decisions. The farm data provided to the decision models therefore combine the user's own information, and that supplied by the DSE. If user costs have not been entered the default values supplied by the system are used.

In addition to the shared data provided by the DSE, the Weed Manager module requires its own private data. There are 2 sets of private data. The first is the data provided with the system and the

second is the users' data. The data provided by the system includes weed and herbicide information. The herbicide information comprises the weed sensitivity, label information, permitted adjuvants and herbicide sequencing and mixing information supplied by the chemical companies and is imported into the database in a format suitable for use by the models (Appendix I). The weed information covers details of all the characteristics of over 140 weed species, the information used to provide help with weed identification, the parameters used by the models to predict the crop and weed growth and the costs of controlling each modelled weed in each crop. This data is used to generate the weed encyclopaedia pages as well as providing data to the system. This data is stored without duplication in a relational structure.

A password protected release version of the database is created for installation. In order to improve the speed of response, some of the raw data is processed during the creation of the release database. For example, the encyclopaedia and biological model both need access to the efficacy data. The process of generating the data in a suitable format requires the use of several queries, which take a significant amount of time. The data is therefore pre-generated in new tables.

The users' data stores the lists of weeds that the user sets up for use on the farms. These lists store the identity of each weed, the number present and the field(s) which use that list.

Database Access
The Weed Manager data is stored in Access databases and is accessed via DLLs. The DLLs have been designed to give the required view of the data to the software and to simplify the process of updating the system if changes to the databases become necessary. The format of the data provided by each DLL is designed to fit the needs of the calling program so a variety of formats have been used.

Internally, the DLLs have a similar structure to simplify future enhancements and bug fixes. All the database access is via ADO. Similar functions are used to provide common functionality such as opening databases and record sets as well as trapping any errors. The variations have occurred because of the slightly varying requirements of each DLL. All the DLLs apart from the one providing the herbicide data to the module report database errors via message boxes.

The herbicide data used by the biological process models is a combination of data from the pesticide database in the DSE and the herbicide and weed biology database in the Weed Manager. When an error occurs the pesticide data DLL returns an integer flag. Each value has a specific meaning. The data from the weed and herbicide database supplied for this purpose also uses an integer flag with the text accompanying the error being generated when an error occurs. The models implementing the spray nozzle selector and the biological processes require native C++ types. The interfaces for these programs have therefore been implemented to return only those types.

The herbicide data shown in the encyclopaedia is a combination of data in the supplied in the pesticide database and the herbicide and weed biology database. All the data is read directly from the database. When the page is loaded, all the required data is read from the database. This includes the list of herbicides for which information is available. The use selects a product and the data is then displayed. In order to provide data in a form that can be sorted and filtered for displaying to the user, the data is provided in ADO record sets.

The wrapper module uses the farm data. Both the DLL and the wrapper are written using Visual C++ allowing the data to be supplied as objects. The classes implementing the objects are defined in a separate DLL. The DLL supplying the user's farm data provides both cropping information and financial information. Models must have values for all the information that is required to perform the calculations. This DLL therefore merges default data with user data where necessary.

Comments on the system architecture

People on different sites implemented the system. This and inevitable time constraints made it necessary to define the system architecture early in the project and did not allow the opportunity to make the changes that were identified as desirable.

The current design of the wrapper providing all the database handling means that the interaction with the OCX is complex and difficult to maintain. In retrospect, the data handling would have been done by a subsystem of the OCX. The toolbar could also have been provided by the OCX. This would allow a simple interface such as

- SetFarmData (data location) – called during start up
- SetWeatherData (data location) – called during start up
- Print() – called in response to the File..Print menu
- Save() – called when the user closes the wrapper or switches to another module.

Separate DLLs are used to provide different views and formats of the data. This has simplified the development of the system because each DLL only provides the functionality needed by the developer of that part of the system. Ideally, there would be one DLL accessing the database that is accessed by the DLLs providing the different views and formats. This would isolate code changes required as a result of any future database structural modification.

Herbicide data import

The herbicide data provided by the chemical companies has to be added to the database so that it is available for use in the encyclopaedia and decision support module. These data have to be updated once or twice a year so dialog applications were written to perform the major tasks required:
- import herbicide sensitivity
- import tank mix data
- import product sequence data
- validate herbicide data

These programs are used by a person responsible for updating the system prior to release of the system, so in this section the term 'user' does not refer to the farmer/adviser using the Weed Manager.

The label data provided by the companies was in a format that could be directly imported into a table in the database.

Herbicide sensitivity data

The data was supplied on predefined spreadsheets. The header of the spreadsheets contained some basic information about the product so that the data could be linked to the correct statutory product information held in the DSE pesticide database. The header also contains the HRAC groups for the product, which is used in assessing the risk of developing herbicide resistance. The rest of the data on the spreadsheet defined the sensitivity of each weed to the product at each stage.

The herbicide sensitivity importer is a dialog-based program. The importing of the data is carried out in a worker thread. The program is designed for level 1, 2 (company data) and 4 (glass house trials) data. In order to check that there are no inconsistencies in the data a herbicide data validation program has been written.

The spreadsheets could contain actual products or generic names. The generic names are converted into actual products, which have the same composition. This is necessary because the module takes the cost of products into account when calculating the efficacy of the treatment.

The Herbicide sensitivity Data Importer interface
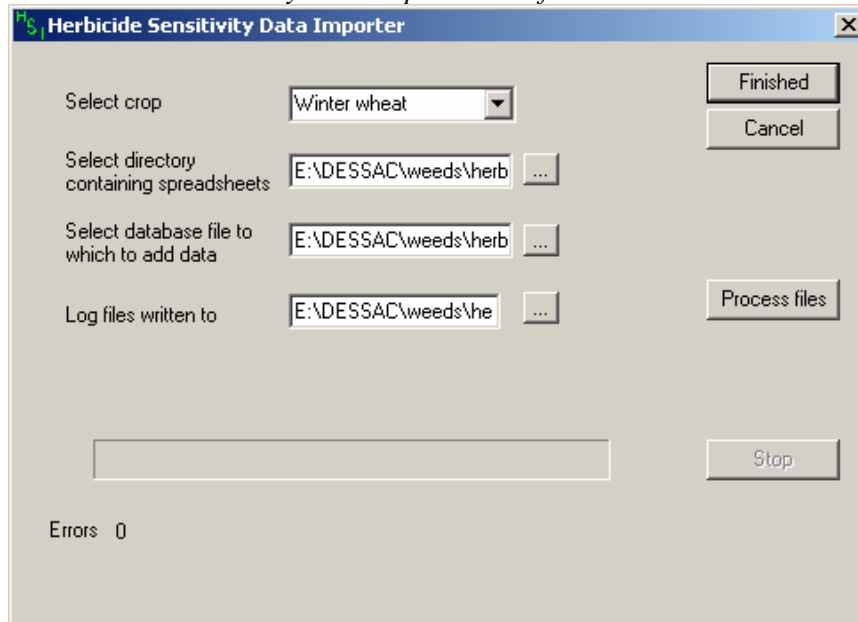
Select crop
The list of crops is filled using the ADO DESSAC shell data server. This means that the DESSAC shell database and the shell server must be installed on the machine. The default value is winter wheat. This selection is allowed to provide for future expansion of the Weed Manager system.

The spreadsheet directory
Use the button on the right to navigate to the directory, or type in the path of the directory, containing the spreadsheets. The program uses only the selected directory. It does not look in subdirectories.

The database file
Use the button on the right to navigate to select the database, or type in the path and name of the database, to which the data is to be added.

The log files
The program writes error messages to a file named *errors.htm* and success messages to a file named *success.htm.* By default these files are placed in the directory containing the spreadsheets. The button on the right can be used to select the directory, or type in the path of the directory, if the reports are wanted in a different directory.

Process files button
After selecting the above information, the process files button is active. Clicking this button starts the processing of the files in the selected directory. When the system is ready to add data the caption on the button changes to pause and the stop button becomes active.

Pause button
Clicking the pause button temporarily stops the files being processed, the caption changes to resume when it is clicked, and then after a pause the program it can be restarted by clicking the button again.

Stop button
This button stops the processing of the data. No data is added to the database if the stop button is pressed.

Progress bar
When the program is working it updates a progress bar. The text above the box indicates the number of files to process and which one it is on. When processing is finished the message changes to 'x files have been processed'.

Finishing
After the files have all been processed the error file and success file are displayed in the default browser. The success file is opened.

Check data consistency
A check is run on the data by using stored queries in the master database. These queries check there are no silly mistakes in the data where a higher dose of a product or a product in a mixture is less effective than a lower dose. Any problems are corrected and the data re-imported.

Tank mixes and sequences
There is a large amount of commonality between the processes of importing tank mix data and sequence data so one dialog based program was written. The user selects the directory containing the spreadsheets to be imported, the database to which the data is to be added and the location for the log files. The program imports tank mix and sequence data only for the products that are known about by the system. The data is stored using the unique ID within the system.
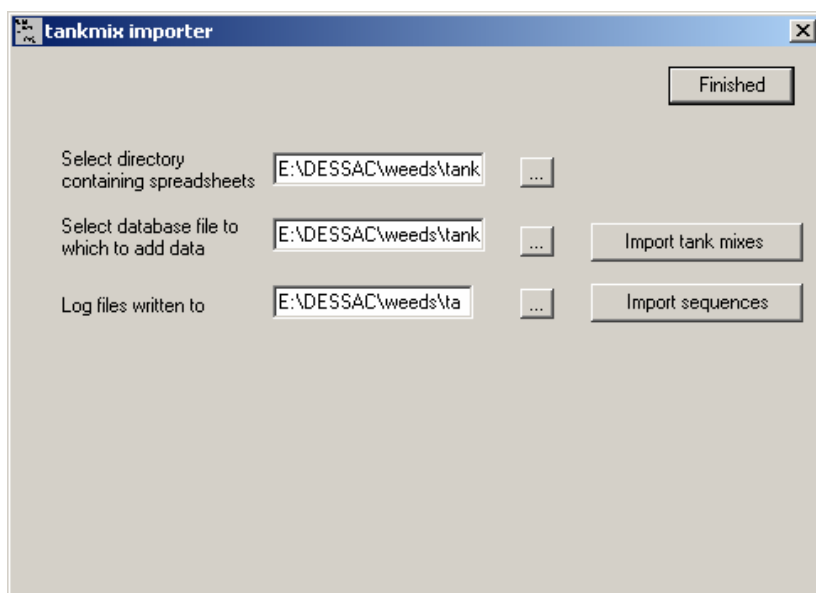
While the program is running, text at the bottom of the window indicates which file is being read or if the data is being written to the database. The log file details where there are problems with the data; this can be due to typing errors adding the names or products being included in the list for which there are no other data.

Validating the data
In the spreadsheets, the activity of the herbicide is given as S, MS, MR, R and G. These letters are converted to numbers for use in the models. In order to ensure that this has been done correctly a dialog based program was developed. After the release database is created, the *validateHerbicideData.exe* program is run to check that the data supplied to the encyclopaedia and the module matches that in the spreadsheets. Some inconsistencies are inevitable because the level 1 and 2 data is provided on separate spreadsheets but these two levels are not differentiated between in the encyclopaedia and module. The output file is manually checked to ensure that the only errors caused are by the merging of the data.

The user selects the data containing the spreadsheets, the database containing the data and the directory to which to write the log file.
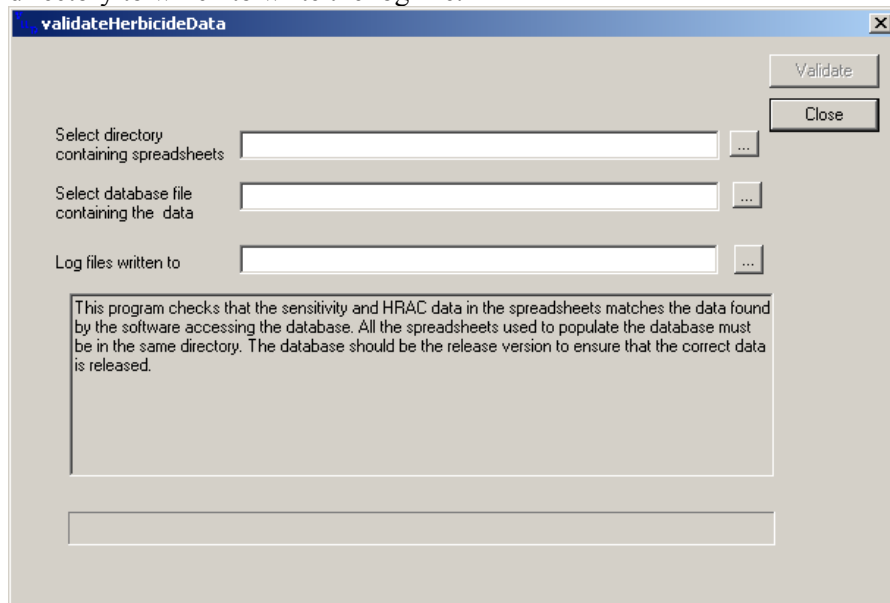
The Resistance Module Summary
Alice Milne, Stephen Moss, Peter Lutman

Introduction
Five species of weeds are considered in the system for potential resistance to herbicides. These are black-grass, wild-oats, Italian rye-grass, chickweed and poppy. The system uses basic rules to decide when a user is at risk and then displays it to the screen. These rules are described below with an example calculation to clarify the methodology.

Method of calculating risk
The user selects a list of weeds they wish to consider in the wizard. Those weeds in the list that are considered to have a potential for resistance to herbicides (i.e. black-grass, wild-oats, Italian rye-grass, chickweed and poppy) are then processed by the resistance module.

Black-grass, wild-oats and Italian rye-grass can be input by the user as sensitive, or as exhibiting metabolic resistance, target site resistance or mixed resistance (ie exhibiting both mechanisms). Chickweed and poppy are input as either sensitive or resistant (target site). The system calculates risk of developing/increasing target site and/or metabolic resistance. The risk of developing/increasing target site resistance in grass weeds is greater than developing/increasing metabolic resistance if HRAC group A (see "Managing and preventing herbicide resistance in weeds – Guidelines 2003" by HGCA, for herbicide functional groups) are used; however this is less commonly seen in wild-oats or Italian rye-grass. Therefore if the user observes any type of black-grass the risk of target site to group A is calculated using higher values (see Table 1). If the user observes sensitive or metabolic Italian rye-grass or wild-oats the lower values are used to calculate the risk of developing target site resistance, but if the user observes target site resistance in these species the higher values are used.

The system considers information from the past 5 seasons (harvest to harvest), if available. Each season is assigned a resistance risk value based on the herbicides used. Herbicides from HRAC group A (these control grass-weeds only) are assigned to category α; from HRAC group B that control both grass weeds *and* broad-leaved weeds to category β1; from HRAC group B that control *only* broad-leaved weeds category to β2; all others to category γ. The risk factors associated with using herbicides from one or more of these categories are shown in the Table 1. These values can be adjusted in the system if risk to resistance becomes commoner.

Time of sowing, cultivation type, and size of weed population are assumed to affect the risk of resistance. These factors are incorporated into the system by scaling the risk value. If the crop is spring sown the risk value for grass weeds only is multiplied by 0.7, similarly if the field was ploughed, or the weed population was set with the lowest infestation level by the user the risk value is multiplied by 0.7.

Table 1. Numeric Resistance Risk Values

Herbicide category	Black-grass target site resistance and other grass weed where target site resistance has been confirmed by the user.	Grass weed metabolic resistance and unconfirmed target site resistance in grass weeds other than black-grass.	Broad-leaved weeds target site resistance.
α	5.5	3	0
β1	3	3	3
β2	0	0	3
γ	1	1	1
α and β1	3.5	3	3
α and β2	5.5	3	3
α and γ	3.5	2	1.0
β1 and γ	2	2	1.5
β2 and γ	1	1	1.5
α and β1 and γ	2	2	1.5
α and β2 and γ	3.5	2	1.5
No herbicides	0	0	0

If no herbicide information is available for one of the seasons the worst case scenario is assumed. The "Overall Risk Value" is taken to be the mean risk value across the five seasons. If there is missing information the user is warned that calculations are based on worst case. If the user has carried out a resistance test on a weed and the results were negative, the "Overall Risk Value" is given by the sum of the risk values since the season the test was carried out, divided by one more than the number of seasons taken into account. The "Over all Risk Value" determines whether the risk of resistance is high ($\exists 3$), medium (>1.6), or low. An example calculation for a high black-grass population and a low poppy population are presented in Table 2.

If no test has been carried out the over all risk values for black grass target site resistant, black grass metabolic resistant and poppy are 2.789, 2.19 and 1.28 respectively which would flag up a medium, medium and low risk.

Table 2. A Worked Example

			Season			Overall Risk Value
	n-4	*n*-3	*n*-2	*n*-1	*n*	
Crop Management						
Cropping	winter	winter	spring	winter	winter	
Cultivation	plough	minimum tillage	plough	minimum tillage	plough	
Herbicides category	no information	α and β1	α	β1	α and β1 and γ	
Weeds						
Black-grass target site resistant	5.5 x 0.7	3	5.5 x 0.7 x 0.7	3	2 x 0.7	**2.79**
Black-grass metabolic resistant	3 x 0.7	3	3 x 0.7 x 0.7	3	2 x 0.7	**2.19**
Poppy (low population)	3 x 0.7 x 0.7	3 x 0.7	0 x 0.7 x 0.7 x 0.7	3x0.7	1.5 x 0.7 x 0.7	**1.28**

The user interface

The resistance module is launched from the within season screen. Those weeds in the users weed list that are prone to resistance (detailed above) are analysed. The current seasons information is determined by what is shown on the within season screen. The crop type is categorised as a winter or spring crop, the cultivation plan is either classed as inversion or non-inversion, and the system is able to determine the HRAC groups for each herbicide in the herbicide plan from information in the database. Where previous seasons information is saved in the database a similar breakdown of information is carried out. This information is displayed to the user on the resistance screen (Figure 1.) If the user wishes to add or change information on cropping, cultivation or HRAC group they may do so. The user can also add details of any resistance testing that has been carried out on their weeds. The system then carries out the calculations above and displays the risk of resistance (in terms of high, medium and low) to the user.

Figure 1. The resistance module screen.

An example page from a herbicide spreadsheet for product Ally.

Product	Ally	**MAPP NO.**	02977	**Version:**	1 **Input By:**	DuPont
Active Name	Metsulfuron-methyl				**HRAC**	
Concentration	200					
Units	g/kg					
Dose:	30	**Units**	g/ha			
Timing:	01/02	None	None			
Wheat GS:	13	39				
LEVEL:	1					

EPPO Code	*Scientific nomenclature*	Common Name	*Priority*	*BLW Growth Stages (lf or whorls)*				
			G Grass	**PRE**	**Cts-2lf**	**2-4lf**	**4-6lf**	**6-8lf**
			B BLW	0-0.95	1.0-2.2	2.25-2.4	2.45-2.6	2.65-2.8
Key Species								
ALOMYs	Black-grass-sensitive	Alopecurus myosuroides -S	G1					
ALOMYm	Black-grass-metabolic R	Alopecurus myosuroides - Metabolic R	G1					
ALOMYt	Black-grass-target R	Alopecurus myosuroides-Target R	G1					
ALOMYr	Black-grass-mixed R	Alopecurus myosuroides-Mixed R	G1					
AVEFAs	Wild-oat-sensitive	Avena fatua-S	G1					
AVEFAm	Wild-oat-metabolic R	Avena fatua-Metabolic R	G1					
AVEFAt	Wild-oat-target R	Avena fatua-Target R	G1					
AVEFAr	Wild-oat-mixed R	Avena fatua-Mixed R	G1					
BRANN	Oilseed rape	Brassica napus ssp oliefera	B1	U	S	S	S	U
GALAP	Cleavers	Galium aparine	B1	U	U	U	U	U
STEME	Common chickweed	Stellaria media	B1	U	S	S	S	S
STEMEm	Common chickweed-metabolic R	Stellaria media-metabolic R	B1	R	S	S	S	S
STEMEt	Common chickweed-target R	Stellaria media-target R	B1	R	R	R	R	R
STEMEr	Common chickweed-mixed R	Stellaria media-mixed R	B1	U	U	U	U	U
Major species								
AGRRE	Common couch	Elytrigia repens	G2					
AVELUs	Winter wild-oat- sensitive	Avena ludoviciana-S	G2					

Technology transfer for Weed Manager

Popular press articles

1. *AgricultureLINK* Magazine (August 2001). '*A Weed Management Support System for Winter Wheat'*.
2. The Hereford Times (May 2003) – '*Open Day focus on Weed Control'* - Advertising WMSS at the Rosemaund Open day 2003
3. Silsoe Research Institute newsletter (March 2004) – '*Decisions Support for Arable Crops'*.
4. Silsoe Research Institute Biennial Report (March 2004) '*DESSAC Weed management Support System'*.
5. Farmers Weekly (August 2005) '*Computerised management aid offers two advantages'*.
6. Farm Business (August 2005) '*Decision support system puts weed management on desktops'*.
7. Crops magazine (August 2005) '*Grass weeds in wheat'*
8. Crop Protection Magazine (August 2005) '*Still room for the plough? Wheat growers can now weigh up the pros and cons of different weed control strategies thanks to a powerful new computer tool'*.
9. Four Seasons - Bayer CropScience magazine (August 2005) 'D*ecisions, decisions: now Weed Manager offers support'*.

Other articles have included reference to Weed Manager and have not been listed specifically above.

Conference presentations and posters (*including papers in proceedings*)

1. **Parker CG, Clarke JH & Davies DHK** (2002) WMSS – Improving Weed Management Decisions. Proceedings *Crop Protection Northern Britain*, 2002.
2. **Parker CG and Clarke JH** (2001) Weed Management: Supporting Better Decisions. Proceedings *BCPC Conference – Weeds*, 2001, Vol. 1:441-448.
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2. HGCA/ARIA workshop, Brooms Barn, January 2003 – Presentation.
3. Association of Independent Crop Consultants (AICC) conference (2004) – Demonstration of the system.
4. HGCA Roadshows – promotional material
5. CPNB Conference (2004) - demonstration
6. LINK Conference (2003) – poster and leaflets (fact sheet)
7. ADAS Rosemaund Open Day (2003 & 2004)- promotional material and demonstrations
8. ADAS Boxworth Open Day (2005) - promotional material and demonstrations
9. SNIFFER/SNH – (October 2005)- presentation and demonstration

Website

www.wmss.net

A spray nozzle selection support system for herbicide applications

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Summary

The spray nozzle selection support system is a computer program that advises on suitable spray nozzles and application volumes for given pesticide tank mixes. The program interfaces with the Weed Management Support System (WMSS), which is a DESSAC module relating to weed control. The DESSAC pesticide database contains product label data that are used by the spray nozzle selection routine.

WMSS first determines the herbicides to be applied. The factors affecting spray nozzle selection are: the target weed, spray quality, drift potential, and application volume. WMSS provides the nozzle selection routine with estimated crop growth stage and type and size of the target weeds. Other relevant information is retrieved from the database. Expert rules are used to generate a ranked list of nozzle types. Once the user has selected a nozzle type from the list, the system interrogates a database of manufacturers' nozzles and returns a list of suitable options.

Key words: Spray nozzle, efficacy, drift, decision support

Introduction

It is well known that choice of spray nozzle can affect product efficacy and spray drift. In some cases advised spray quality and nozzle type are specified on the product label. Literature also exists, such as the HGCA nozzle selection guide (HGCA, 2002), to help farmers decide which nozzle type to use. The spray nozzle selection support system is a computer application, which draws together label information and expert rules, to evaluate which nozzle type is most appropriate for a given circumstance.

The spray nozzle selection support system has been developed as part of the Weed Management Support System (WMSS). WMSS is a computer-based decision support system designed to help farmers and advisors with weed management. It aims to improve targeted weed management for cost benefit, reduce environmental impact and encourage biodiversity. The system includes an 'in-season' decision support system that allows the user to investigate the affect of different herbicide plans on weeds in a winter wheat crop. It also includes a rotational system that predicts the impact of cropping and cultivation on weed populations. The spray nozzle selection support system interfaces with the 'in-season' part of WMSS. WMSS has been designed to be a component of DESSAC (Decision Support System for Arable Crops). DESSAC was developed with the aim of integrating a suite of computer-based decision support modules so that common data can be shared (Brooks, 1998). These data include local farm and weather data, pesticide and crop variety data. Amongst the data stored in the pesticide database is information relevant to nozzle selection such as spray quality

and advised application volume. This information is retrieved and utilized by the spray nozzle selection program.

The spray nozzle selection program operates in three phases. In the first, expert rules are used to generate a ranked list of nozzle types for the specified tank mix. Then in the second phase a range of suitable application volumes are defined either from product label information held in the pesticide database or by the user. From this a range of application rates is derived. In the final phase the user selects a nozzle type from the ranked list and the system retrieves suitable manufacturers' nozzles from a local database, which fit with both nozzle type and flow rate specification.

Materials and Methods

Generating a list of spray nozzle types

The methodology used to generate a list of suitable nozzle types for the target problem is based on the HGCA nozzle selection guide (HGCA, 2002). This guide provides a lookup table for farmers to evaluate spray nozzle types based on their affect on pesticide efficacy and drift control. The nozzle selection guide indicates the spray qualities (Southcombe *et al,* 1997) that each nozzle type can typically achieve. It also indicates levels of drift control that would be expected from each nozzle type. Spray drift is classified as "high", "moderate" or "low", and for each target type the nozzle giving the lowest level of drift with acceptable efficacy is also identified. It also indicates how the efficacy of a pesticide is affected by choice of spray nozzle. For example a conventional flat fan nozzle offering a fine quality spray will potentially be more effective than a nozzle of the same type offering a medium quality spray when targeting grass leaf weeds with less than three leaves.

Defining the target problem using the decision module output.

The WMSS system evaluates an herbicide program (which may consist of more than one spray application) for a given field situation. The spray nozzle selection system can then be run to evaluate suitable nozzle types for any of the spray applications. The choice of nozzle type is dependent on the size and type of weeds being targeted. The user interface allows the user to define the target weeds. However, Parker (1999) found that the uptake of decision support systems is hindered if they require too much initial data entry, and that where possible it is better to provide sensible default data. Therefore, although the calculations may at first appear perverse, the nozzle selection program has been designed to deduce the target problem from information passed to it from the WMSS module. The information provided by WMSS is the list of herbicides in the tank mix, the date of spraying, target crop (which currently is always winter wheat), estimated crop growth stage on the date of spray application, the list of weeds in the field and estimates of their respective growth stage on the date of spraying. Each herbicide is evaluated in turn. Firstly the database is queried to establish if the main mode of action for the herbicide is soil and/or foliage acting. If the herbicide is foliage acting its active components are retrieved to see if it contains glyphosate, glufosinate ammonium, paraquat or diquat. If this is the case the herbicide is assumed to be non-selective, if not then the target weed types are evaluated. This is done by considering the efficacy of the herbicide against each of the weeds in the weed list. If a weed is moderately sensitive or sensitive to the herbicide then the system assumes it is targeted by the herbicide application. The weed growth stages provided by WMSS are defined in terms of the number of leaves on the weed. In the case of broad-leaved weeds a growth stage description in terms of the size of the weed across is more appropriate to consider when deciding on nozzle type. Therefore expert opinion was used to convert between the two (Lutman – personal communication). The conversion for a subset of the weeds covered in WMSS is shown in Table 1. These data are currently being validated as part of a field experiment (Storkey – personal communication). Details of the assumptions made about target problem are displayed to the user, who may override them should they wish to.

Table 1. *The conversion between number of leaves on a weed and weed diameter*

Weed Name	Leaf number at 2cm	Leaf number at 5cm
oil seed rape	1	5
fat hen	2	5
cleavers	1	5
knot grass	2	6
chickweed	4	>8
common poppy	3	8

The spray nozzle selection program allows the user to add other pesticides to the tank mix. Comprehensive lists of crop specific herbicides, fungicides and insecticides are retrieved from the pesticide database and displayed to the user. Any of these may then be added to the tank mix, although if the new tank mix does not appear in the system list of recommended tank mixes a warning is displayed to the user.

Assigning a score to each nozzle type

For each pesticide in the tank mix the manufacturer recommended spray qualities are retrieved from the pesticide database. The system evaluates compatible qualities for the pesticide tank mix, and uses this information to cut down the nozzle type search space. If there is no information or incompatible spray qualities are found the search space is not reduced. Given the target problem or problems, the system then evaluates the remaining nozzle types assigning scores based on efficacy and drift control. The scores S are calculated using the equation

$$S = \left(\prod_{i=1}^{N} (1 - \delta(E_i)) \right) D^p \sum_{i=1}^{N} E_i^{2-p}, \qquad 0 \leq p \leq 2 \tag{1}$$

where $\delta(E_i)$ is the dirac delta function which takes the value zero for all values of E_i except for when $E_i=0$ where it equals one, and $\prod_{i=1}^{N} (1 - \delta(E_i))$ defines the product of the N, $(1 - \delta(E_i))$ terms. The parameter E_i is the efficacy score for the nozzle against target problem i, D is the drift score for the nozzle, and N is the number of target problems. The default assumption is that the user will want to consider a balance of efficacy and drift. However should they wish to, the user is able to specify a relative preference for efficacy or drift control. Parameter p defines how the user prioritises drift and efficacy. The default setting is one. The efficacy score E takes the value 2.0 for preferred nozzles based on efficacy, 1.0 for nozzles offering acceptable efficacy, and 0.0 otherwise. This means that if the nozzle offers less than acceptable efficacy against one of the target problems the total score for that nozzle will be zero. As containment of drift is classified by a logarithmic scale (Miller et al, 2002), the drift classes are allocated values of 1.0 for high, 1.66 for medium and 2.0 for low. The nozzles are ranked according to the score they achieve and displayed to the user in order of preference.

Defining a suitable range of flow rates

For many of the pesticides, the label recommended range of application volumes is held in the pesticide database. The system retrieves this information and displays it to the screen. The range of volumes for the tank mix is calculated as the intersection of the component volume ranges and is displayed to the user in an editable form. A range of suitable flow rates are derived using the equation

$$f = (v \, s \, d) / 600, \tag{2}$$

where f is nozzle flow rate (litres min^{-1}), v is application volume (litres ha^{-1}), s is forward speed (km h^{-1}) and d (m) is nozzle spacing on the boom. Default values of 12 km/h speed and 0.5 m nozzle spacing are assigned, although the user can alter both.

Retrieving Nozzles from the database of manufacturer nozzles

Once nozzle type and desired flow rate have been decided the user can select a suitable nozzle from a manufacturer's catalogue. Alternatively, the system offers information on nozzles from a limited number of manufacturers. The information is stored in a database and includes the name of the nozzle, the ISO classification, minimum (P_m) and maximum allowable pressures, minimum flow rate (f_m), and lowest and highest pressures at which the nozzles can attain a given spray quality class. From this information all viable flow rates for a given spray quality can be calculated using the interpolation formulae

$$f = f_m \sqrt{P / P_m} \tag{3}$$

where *f* is the flow rate defined to occur at pressure *P* and f_m is the flow rate defined to occur at pressure P_m. The system uses database queries to retrieve all the nozzles in the database of the user specified type that operate within the defined flow rate. The system displays the nozzle types along with a recommended pressure, application volume and speed to the user. The pressure is rounded to the accuracy of the user's pressure gauge and the volume is adjusted to compensate.

Results

To illustrate the result of using the system we consider the example of an application of the herbicide Panther (isoproturon + diflufenican) (Bayer Crop Science) applied on 15 November. The output from WMSS tells the spray nozzle system that the crop is winter wheat and that the weeds the user is concerned with are *Alopecurus myosuroides* (black-grass), a grass weed, and *Stellaria media* (chickweed), a broad-leaved weed. At the time of the spray application the estimated crop growth stage is Zadoks 11 (Zadoks *et al*, 1974) and the estimated growth stages for black-grass and chickweed are Zadoks 11 and over 4 leaves respectively. At these growth stages black-grass is considered resistant to Panther and chickweed sensitive. The data on Panther in the database specifies that it should be applied with a medium spray, that the main mode of action is foliage acting, and that does not contain any actives that would suggest it were non-selective. Therefore the system deduces that the spray is targeting chickweed at a 2-5 cm across (see Table 1.) This defines the target problem. Using equation 1 the system evaluates each of the nozzles and ranks them according to score. The system output is shown in Fig. 1. The screen shows the assumptions made about the desired spray quality and target problem. If the efficacy/drift slider bar is moved the ranking of the nozzles changes. Fig. 2 shows the affect of moving the slider bar on the preference ordering of the suitable nozzles.

The second step in the calculation is to evaluate the flow rate range. Information retrieved from the database states that the range of application volumes should lay between 200 – 400 litres ha^{-1}. With default nozzle spacing and forward speed the range of flow rate is 2.0 – 4.0 litres min^{-1}. Now that suitable nozzle types and a range of application volumes are defined a manufacturer's nozzle can be selected. The results for air induction type nozzles are shown in Fig. 3.
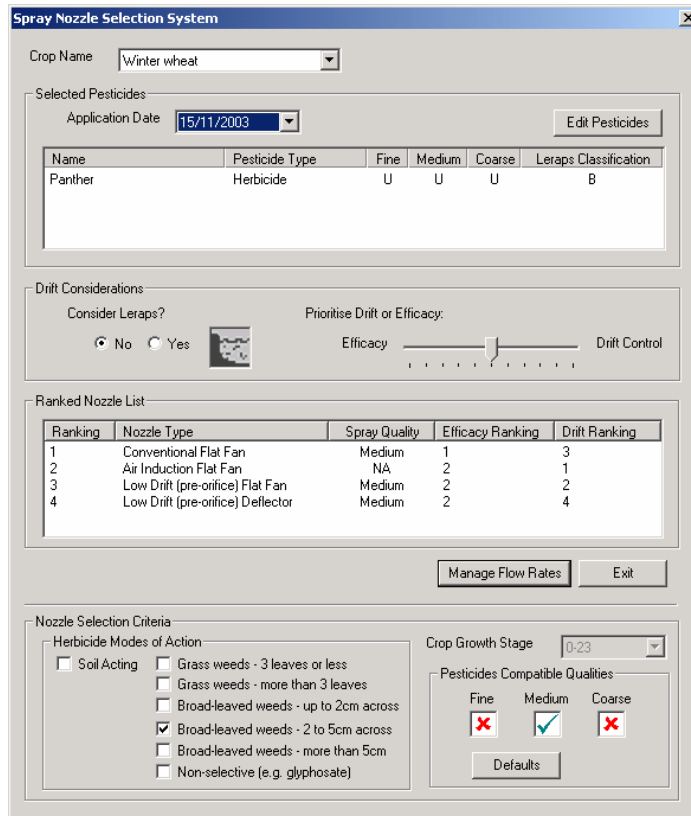
Figure 1. The spray nozzle selection system main screen.

relative preference for efficacy and drift (p)
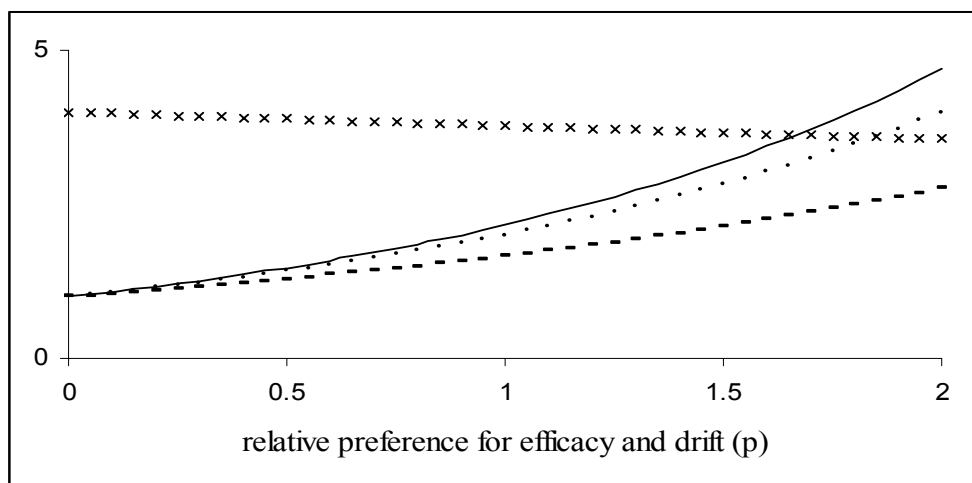
Figure 2. The affect of changing the drift/efficacy priority on nozzle ranking. The *x*-axis is the slider position with the far left indicating a high preference for efficacy and the far right a preference for drift. The *y* – axis is the nozzle score. Air induction ▬, low drift flat fan ∙∙∙, low drift deflector - -, conventional flat fan x x.
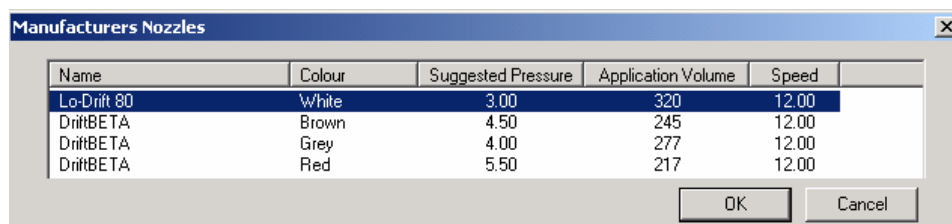
Figure 3. A list of air induction nozzles from different manufacturers with suggested pressure, application volume and forward speed.

Discussion

The spray nozzle selection program aims to give decision support as to which spray nozzles and application volumes are suitable for a given tank mix of pesticides. It allows the user to explore which nozzles are more appropriate when considering a balance of drift control and efficacy. Decision support systems are not designed to make an absolute decision, but instead they collate and process relevant information and interpret and communicate a range of suitable options to be used in the decision making process.

Although designed to interface with WMSS it was straightforward to include nozzle selection rules relating to fungicides and insecticides as well. Therefore the programme has been written in such a way that it could interface with any pesticide selection DESSAC module. The system illustrates the potential value of infrastructures such as the one provided by DESSAC as it shows how simple systems can be produced to process extensive data and provide information to the user in a comprehensive way. It would take a lot longer for the user to lookup relevant information in catalogues and charts and make a decision than it would to run the system. The speed and ease with which the system provides the user with the information they need to make a decision should improve decision-making. Systems such as the one discussed here could play an important role in the transfer of knowledge on the importance of nozzle selection to the end user.

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Project Report No. 388
(Appendix L)

February 2006

Development and validation of 'Weed Management Support System' (Weed Manager)

by

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APPENDIX L

User reports by Glasgow Caledonian University

WMSS
User Group Activities
Nov 2002 – March 2003

GLASGOW

C

CALEDONIAN

UNIVERSITY

Caroline Parker
Caroline Park
28th March 2003

Section 1

Table of Contents

1   Introduction

This document describes the user-based activities carried out within the WMSS project between the period November 2002 and March 2003.

Two user workshop activities were scheduled during this time, the first to take place in the second week of November 2002 at ADAS Wolverhampton and the second at ADAS Leeds in the second week of February 2003.   An email-based consultation also took place immediately after the second workshop.

The purpose of this document is to collate the data from these three user activities and to outline the main changes to the design suggested by it. The intended audience for this document is the WMSS design and development team.

2   User Workshops at Wolverhampton and Leeds

Although both events were planned along the lines of previous workshops i.e. two groups per day and 6-8 people per group, the number of individuals who actually attended were considerably lower than expected. On the day two people attended the Wolverhampton event (one farmer, one consultant) and five people attended the Leeds event (three consultants, two farmers).

The format of the workshops was similar at each event and ran as follows:
- Introduction
   An introduction to the WMSS project and the function of the workshop.

- Model based system overview

A walk though of the current system interface design and functionality using screen shots and drawings in a Powerpoint™ presentation during which the participants were encouraged to make comments and ask questions.

- Hands on feedback with questionnaire

A session in small groups in which the participants worked their way through tasks and questions and had some time to play with the functional components of the system. The key areas examined by the users in this session were:

   Single season view
   Weed list dialog
   Observations dialog
   Suggest treatments dialog
   Encyclopaedia (product and weed biology)

There was more focus on the encyclopaedia in the February workshop than the one in December and some elements of the single season view had been updated from the previous event. A final session looking at the visual display of weed density was also included in the February workshop.

2.1 Results from user workshops

Overall the main features and functions of the WMSS system were well received and the changes suggested were related to the way in which users wish to interact with the functions rather than with the functions themselves. The short season screen was seen as useful and not too cluttered but there still were issues of understanding with the rotational planning screen. Users appear to find the concept of long term rotational planning for weed management somewhat alien and until they are able to interact with this screen directly it will be hard to tell what aspects of the problem are due to this and what to screen layout and design.

The detailed results of the workshop discussions and hands-one sessions are collated here under screen function headings. Where problems were found these are listed and user suggestions for solutions and additions are also presented. Those changes considered important are listed under the heading 'Suggestions for changes to design' in each section.

2.1.1 Opening WMSS

All users in both groups found this easy to do. No changes suggested.

2.1.2 Creating a weed list

There were some problems with the design of the weed list. Some users did not find it easy to set a list up.

The problems users identified were:
- Wanting to identify a field before setting up a weed list
- Not knowing how to create their own list from the list provided.
- Being prompted for a list name because they clicked OK to enter a weed
- Being confused by the number of weeds with similar names
- Not understanding the use of the terms 'sensitive' and 'r' next to a weed name
- Finding the font sizes too small
- Two users in the second group preferred the word 'unknown' to 'no observation'

User suggestions:
- Use 'unknown' instead of 'no observations'
- Move 'unknown' to the bottom of the button list
- Weeds to be listed by common name and in alphabetical order
- To have more mouse over information in this dialog
- Four out of the seven participants wanted all weeds to be listed but to have some way of highlighting those that had models associated with them, the other three wanted only modelled weeds to be listed.
- Two users in the Leeds group would have preferred < and > to be used in the density buttons

Suggestions for changes to design:
- Use a default weed list name and allow the user to change it on leaving the weeds list window
- Move 'unknown'/'no observations' to the bottom of the button list
- Use a short instruction to appear in/on top of the top half of the dialog e.g. 'highlight a weed name and click on a number button to add to your list' to guide the user. If possible allow this instruction to be removed by the user.
- Spell out the word resistance rather than using 'r'
- Make sure that help from this screen explains the different types of weed.
- If possible provide a pop-up for the window explaining the different types of weed.
- Use a larger font size for dialogs if consistent with Windows guidelines

- List weeds by common name and in alphabetical order
- Highlight (bold text?) weeds that are modelled

2.1.3 Plant observations dialog

There were some problems with the design of this dialog although users were happy with deleting weeds.

The problems users identified were:
- Four out of the seven participants had problems finding the dialog.
- Two participants couldn't see the image on the icon because of its small size on their screen.
- Two participants felt that the image was too close to the zoom icon used in Windows to be obvious.
- One group couldn't input GS21 and 22 for winter wheat

User suggestions:
- Have a pop up box from the main screen for observations
- Have mouse overs on % kill and yield loss bars (call this 'control gain')
- Add units to yield and margin
- Leeds participants wanted to see more than one observation for each weed so you know if the weed changes after being sprayed. Possibly create a spray diary.
- Leeds users suggested having an indicator on observation screen showing when a spray has taken place (puts weed levels in context)
- Three participants wanted to see last observation on the screen as well as the spray plan so they can identify reasons for the drop in density. The other two were unsure.
- Define what mean by density – per square meter, % cover, GAI?
- One farmer felt that there was no need to use both density and cover and that cover was more usually associated with crops not weeds.
- Both Wolverhampton participants said that different weeds have different measurements e.g. number of leaves or diameter.

Suggestions for changes to design:
- Change the icon for this function and increase size if possible (check icons used in popular CMS for this type of function)
- Have mouse-overs on % kill and yield loss bars to explain their content
- Add units to yield and margin
- Rethink observation dialog to see if last spray information could be included without cluttering
- Allow users to see previous observations
- Define density – on screen or as pop up
- Make wheat observations distinct from weed observations – grey space or line separating?

2.1.4 Adding a spray manually

There were some problems with the design of this dialog, although users were happy with the way products were listed and with deleting sprays.

The problems users identified were:
- Users on the smaller screen at Leeds found the icon hard to locate.
- Two users in the second workshop and the farmer in the first workshop found it hard to add a second spray to a single date
- Several users suggested that not being able to enter a specific rate would be a problem

User suggestions:
- Both Wolverhampton participants felt that the dose rate had to be flexible rather than being the manufacturers recommended dosage.
- Adding another product should default to the first date
- The two users with the smaller screen wanted the font and text box size to be increased.
- Add a form of unit to the numbers
- Two Leeds users wanted the scale to read full dose, half dose etc.
- Both Wolverhampton participants felt a different colour should be used for yield loss and margin
- Both Wolverhampton participants felt that the length of time till the spray kicked in should be modelled.

Suggestions for changes to design:
- Allow users to pick products and then pick a date on which to apply it
- Allow user to put in the exact dose applied
- Increase text box and font size if in accordance with Windows guidelines
- Add a unit to the numbers
- Increase size of icon

2.1.5 Suggested treatments list

There were some problems with the design of this screen although all participants but one found the screen easily and knew it illustrated the best options. No-one had any trouble identifying the spray plan, dosage and application date for their chosen plan. Overall users were happy with the screen layout and felt that it was not too cluttered.

The problems users identified were:
- Both users in the first group were worried by the yield calculations believing them to be inaccurate
- All users were confused by the highlighting colour initially
- All second group users found it hard to say what the yield was for a chosen plan.
- Leeds users suggested that sometimes they might not have the equipment on the farm to make the suggestions relevant!

User suggestions:
- The farmer in the first group thought that it would be more useful to show the mix details rather than when to apply them and that the price was not obvious.
- The farmer in the first group thought that it would be more useful to compare two at a time
- Double click to choose a plan
- All second group participants want a 'no spray' option to appear so they can compare between action and inaction. They said that this would be reassuring for them.
- Two of the second group farmers would like to specify spray windows in which they would consider spraying
- Two of the second group suggested mouse overs showing yield for a selected plan, they also would like yield to go up to 15.
- Participants would like a mouse over for each spray arrow to indicate what spray plan is being used.
- Would like IPU to be added.
- Two second group participants indicated that they thought the efficacy spread and strength indicator was good, but it wasn't very clear on the current display and it didn't expand when the timeline was stretched.
- One consultant indicated that he would use it on a field by field basis to test out ideas and assumptions. Especially useful for unusual and difficult situations.

- One farmer indicated that he knows his own farm very well and it is very similar year on year, for this reason it would not be as useful to him. He would however use it as a back up to the consultants' advice and his own thoughts.
- In the ptimisation results screen session 1 participants felt that two colours were not required for the margin bar, one is sufficient as they know the mean will be in the middle of the bar.

Suggestions for changes to design:
- Change the highlighting method to look more like a highlight and less like a different option (different tone of same colour?) Make colour go all across option and not just centre panel.
- Allow users to double click to select a plan
- Put the 'no spray' option on the bottom of the screen even if much lower than rest of items on screen
- Allow users to specify a spray window to constrain the model
- Pop ups over spray icon to show spray contents and date
- Make sure that efficacy stretches with time display
- Add IPU?

2.1.6 Single season screen

Overall workshop participants were happy with this screen. Some suggestions for improvements were made:

User suggestions:
- Default to showing the whole season – some users found it confusing to see only a few growth stages.
- A mouse over the yield loss scale would be useful
- Wolverhampton users wanted to see mouse overs used with the yield loss and % kill bars,
- All users wanted positives rather than negatives used for % kill.
- Wolverhampton users wanted a mouse over on weeds to let them know if it has been sprayed and when.
- Use single colour bar (Leeds) rather than showing gradiated bar and mean.
- All participants wanted to see population density in preference to growth stage on the screen but the majority would like the choice to see either.
- All of the Leeds group wanted to see crop density displayed as a mouse over.

Suggestions for changes to design:
- Default to showing the whole season
- Provide a mouse over for yield loss and % kill areas showing meaning
- Express % kill as positive rather than negative
- Provide a mouse over the spray icon to show contents and if sprayed
- Show population density in preference to growth stage give users choice to see either.
- Show crop density displayed as a mouse over

2.1.7 Full rotation screen

There were some problems identified during the walkthrough of this screen.

The problems users identified were:
- Session 1 users found it hard to tell what the screen was trying to show them.
- Both groups felt that a long rotation look ahead was a problem. The users from Wolverhampton felt that it would be hard to plan a full rotation as it varies so much year on year. Leeds users were also not used to looking that far ahead – make decision on what to drill at last minute

- Soil type information is missing. Both Wolverhampton participants want the soil type to be displayed as it impacts what chemicals can be used. They suggested that the last harvest date was not important so use that space for soil type.
- No indication of what margin relates to.

User suggestions:
- Both groups felt that competitiveness and contamination were two of the three most important icons. The first group thought that resistance was also key and the second group that some indicator of general environmental impact was most important.
- Leeds users felt that it was important that they system picks up data from the crop management system
- All users were not interested in figures in pounds just an indication of direction
- The session 1 consultant felt that the weather has to be input into the rotational planning as it has a huge impact.
- Consultant (session 1) questioned value of seed return as this is not important with some weeds
- Consultant (session 1) wasn't sure why anyone would be interested in an individual weeds yield loss figures
- Consultant (session 1) suggested that impact of not ploughing on soil nutrients should be highlighted (WRO work), have to plough every 3/4 years and this system might discourage that.
- Both (session 1) users felt the system would be useful in completing voluntary plan forms
- Consultant (session 1) wanted to see something closer to the Farmade layout and view either one year or all years, toggle between them.

Suggestions for changes to design:
- Make sure that training and help for WMSS focus on importance of looking ahead over rotation and usefulness in planning
- Include soil type in set up
- Add pop up over margin to explain what margin value is
- Use competitiveness, contamination, resistance and an indicator of general environmental impact as key icons
- Make sure help system describes variables used in models and why others (eg weather) may not have been.
- Check format/content of voluntary initiative documentation to see if WMSS could generate reports in useful style

2.1.8 Encyclopaedia pages

Product page design
There were problems with the design of this page.

The problems users (Leeds only) identified were:
- Participants felt that it was too segmented.
- Felt that the headings were not clear and they had to split on each to see the drop down. They wanted the most important things up top so they could go straight to them.
- They thought the information was useful but rates had to be included as that was the most important thing.
- Formulation is not critical.
- The two participants using the smaller screen thought the font was too small.
- All thought the tank mix was vital and they couldn't find it. (this was supported by walkthough discussion at Wolverhampton)

User suggestions:
- Two participants thought that a reference indicating where information came from would be useful, and did not want to see information that was not authorized by the company.
- One farmer wanted the rate of inclusion – list of ingredients and rate of concentration.
- Wanted a choice as to whether to close all windows at once or one at a time.
- All participants want English names to be used, and for them to be listed alphabetically by name and then by sensitivity.
- One user suggested that if non-company information was in this section the reader should be prompted to check with their advisor before using.
- Two of the participants came up with the concept of top tips being on the front page. This should contain
  - ➢ Rates.
  - ➢ Crops it can be used on.
  - ➢ Crop growth stages.
  - ➢ Leraps or not.
  - ➢ Latest spraying dates to harvest.
  - ➢ Crop restrictions, following crop restrictions.
  - ➢ Tank mixes (compatible).

(this suggestion was tested in an email poll of users and the results are presented in the next section)

Suggestions for changes to design:
- Create a front page with most important information on it (see next section for headings)
- List products by English name alphabetically and then by sensitivity
- Include rates
- Include information on tank mixes if at all possible
- Check display on smaller screens and increase font/icon size if consistent with Windows guidelines
- Try to break down into more tabs so that can remove drop down arrows where possible to get all text on the screen.

Weed biology page design

There were no problems with the design of this page. "Whoever designed this was a genius" all participants found everything really easily and loved the pop up screens. All participants found the information useful – particularly for unusual weeds. There were some suggestions for improvements.

User suggestions:
- Two participants would like to be able to have two windows open at a time as to allow for a comparison. The other two were unsure.
- The two participants who used the smaller screen thought that the images of adult plants could go to full screen on click. The seedling images were fine as they were. Full size screen for unusual or easily confused weeds would be advantageous.
- All users wanted English names to be used as the index but two users wanted the choice of using Latin as well.

Suggestions for changes to design:
- Provide full screen images of adult unusual/easily confused weeds
- Use English names for indexing (Latin as option in version 2!)

2.1.9 Estimating cover screens

In order to support the user in estimating weed cover images of weeds in wheat will be used. Participants at Leeds were asked which of several types of weed cover images they preferred.

Overall users preferred the images where weeds were replaced by yellow colouring because it was so easy to see the weeds although they felt that the hue change option might give a more accurate picture. They would prefer to have both options if given a choice.

2.1.10 Possible bugs in the system

In the weed list screen when the return key is hit after entering the weeds, it leaves the weed dialogue and the weed list is lost.

3. Top ten product information items – email consultation

		No. mentions	No. top 3
1	Crop Growth stages	19	2
2	Compatible tank mixes	18	12
3	LERAPS	18	5
4	Latest spray dates to harvest	18	2
5	Crops to be used	18	
6	Following crop restrictions	17	2
7	Rates	16	
8	Soil/Weather limitations	8	8
9	Important weeds controlled	8	
10	ai	7	7
11	Max rate of use/ no. treatments	4	3
12	Type of formulation/ concentration	3	3

In response to the Leeds users suggestion that the product pages be improved by adding a 'top ten' list an email was circulated to the WMSS user contact list asking for feedback on the most important items. Contacts were asked to list the items of information relating to product that they felt were most useful and to rank these in order of importance. As both the degree of interest and the degree of importance of an item will be used to make the decision about use both aspects are shown in the table above. Estimate of importance is provided by a count of those respondents rating the item in the top three.

Based on the information returned it would be suggested that the following be listed on the front page in order of precedence:

1. Compatible tank mixes
2. LERAPS
3. Crop Growth stages
4. Latest spray dates to harvest
5. Following crop restrictions
6. Crops to be used
7. Rates
8. Soil/Weather limitations
9. AI

10. Important weeds controlled

If space permits then the following can also be considered:

11. Maximum rate/number of treatments
12. Type of formulation/concentration
13. Trade name (2, 2)
Weed growth stages (2, 2)

WMSS
Training Session Results
December 2003

Caroline Parker
Caroline Park
8th January 2004

SECTION 2

Table of Contents

Introduction

This Document summarises the results obtained from the user-based activities carried out within the WMSS project during November and December 2003. A copy of the WMSS software (version 1U) was distributed to a group of around 50 users during November, the users were asked to try using the system and feed back their opinions and any faults they found with it.

Four training sessions were held, one at ADAS in Leeds, two at Silsoe Research Institute and one at ADAS Rosemaund. The training sessions were split up into three main sections. The first section involved giving the users a walkthrough of the WMSS in season screen, and explaining the functionality of the various screens within it. The second part of the day was a hands on session. Here each of the participants were given a workstation and asked to work through a task sheet. The ease with which the participants completed these tasks was monitored. In the third part of the day the users were introduced to the strategic planning screen and instructed on how they might use it when it becomes available to them and were invited to give their opinion on it.

The purpose of this document is to collate the data from the users and to outline the areas which were pinpointed as being problematic; any bugs found within the system during the exercise are also be identified.

1   Training session results

Although we were planning for an attendance of 6-8 people per session, unfortunately the actual attendances were rather lower. On the day two people attended the morning session at Silsoe, (one farmer, and one consultant) and three attended the afternoon session (One farmer, two consultants). three people attended the Leeds session (Three consultants) and two people attended the Rosemaund session (two consultants).

1.1   Main In season screen

Overall the main features of the in season screen were well received. There were however a few problems identified by the users, these are listed below in the form of suggested changes to the current system.

   Requested changes were:
   - Insert some form of title into the in season screen and the rotational screen as when users were working on the in-season screen they did not know that is what they were working with till we told them – put a title at the top of the screen saying in-season or rotational.
   - Add mouse overs to the wildlife icons in the in-season screen to explain what they mean.
   - Ensure that when the main screen opens it is in maximised form.
   - Add a pop-up/mouse over to spray icons on the date line to say what was in that spray.
   - At the top of the screen the first drop down box should be field rather than weed list as users said that the field would be their first thought.
   - At the moment you have top go through the wizard to access a weed list and settings. Users did not find this very intuitive – add a separate icon to the screen for each of these functions
   - Users want to be able to save spray plans and name it what they like.
   - Users want to be able to print out a list of sprays and cultivations for any given plan – add a print icon to this screen.
   - Users would like to be able to click on the spray icon as well as the arrow below it to move a spray in time.

- Users want to be able to have more than one screen open at the one time and minimise "the way you can in windows".
- At the moment when you start up the system you get a changes popup appearing saying that changes have been made. We have to stop this appearing as it damages the users initial perception of WMSS.

The positive comments were:
- Users liked the expand time function.
- Users liked the time warp function.

1.2 Wizard

There were a few problems identified with this part of the system. The users were however happy with the way the weeds were listed and selected.

Requested changes were:
- Give users the ability to edit an existing weed list and save it with a new name.
- Explain the measurement of crop density next to the density entry area.
- Remove the last page on the wizard because it is redundant and adds an additional step.
- Provide some explanation to users of why you need to enter a number for weed population at the start (possibly pop-up?).

1.3 Observations

Overall the users found this screen useful but there were a few suggested changes.

Requested changes were:
- You should not be able to enter cover or density if no GS has been entered – grey out density and cover boxes until a GS has been entered.
- Provide some instruction on screen to tell the users they only have to enter cover or density and not both.
- If they have to choose between them then users would rather use density than cover.
- In the results screen the words 'treatment program' or 'program treatment' should be used rather than just 'treatment' as at the moment it seems like it all goes into one tank mix.

Other problems were:
- Users were unsure of how to measure density and cover, especially cover.
- Observations were not saving to the database.

The positive comments were:
- Users liked having the ability to scroll to see past observations.

1.4 Optimisation

The users liked this screen, though they did find that it made some rather strange suggestions (see section 3)

Requested changes were:
- Provide facility to click on the Treatment name section in order to select a plan rather than just being able to click on the orange bar.
- Provide facility to be able to drag and drop he black triangles to see the effect on yield/margin.

1.5 Add Sprays

Many of the users found it difficult to come up with a combination of sprays that the system would accept, but had no problem with navigating the screen.

Requested changes were:
- Provide the facility to add different rates as users say they rarely use the manufacturers recommended rate and find the restrictions placed on them by the system extremely annoying.
- System should allow you to apply mixes even if they are not recommended as this is something that the users do on a regular basis.

1.6 Add Cultivations

Users found it easy to navigate and understand this screen. Some changes were requested

Requested changes were:
- Direct Drill – this is not the preferred sowing method. They hated being constrained to this and kept trying to delete it. Should just call it sowing and allow direct drill as an option.
- Allow Harrowing after drilling – is not currently allowed and should be.
- Cultivation error messages relate to sprays and not to cultivations, this has to be changed.
- Users want a warning to appear if they choose to harrow a crop and there are residual treatments on it.
- Sub-soiling should be in the cultivations list.
- Change the central movement indicator (currently a one) to an arrow, the current symbol makes no sense to the users
- At the moment you can only add one cultivation a day – The users found this very annoying as they often perform more than one a day.

1.7 Encyclopaedia

All of the users loved this feature of the system. They thought the layout, and the information contained within it was fantastic. They did however find a couple of possible problems.

Requested changes were:
- It is not made clear anywhere that everything within the encyclopaedia refers to winter wheat. The data held within the encyclopaedia could change according to what crop it refers to (especially yield loss).
- The weed information tab is always the default when you hit the back arrow rather that the tab you were in before.

Possible Faults:
- Do common poppies germinate from 5cm?
- Can barren brome germinate from 130cm?

2.0 System Faults

We asked all of our users to take note of any faults or discrepancies they found while using the system. The ones they found are listed below.

2.1 Unacceptable outputs/inputs

The system gave some strange suggestions to the users and also seemed to not be calculating the effectiveness of some chemicals properly.

Discrepancies:
- Touchdown Quattro does not seem to work on Couch – it should do.
- Spring tine was being suggested in December.
- You should not be able to apply Crystal post emergence.
- It allows Hawk 2.5 plus adjuvant and Stomp 400 at 2.5 to be mixed – this is not legal.
- BG and Crystal are not working properly, Crystal should be put on pre-emergence – in the system it works better when it is applied later, this is apparently wrong.
- Hawk and Lexus could not be mixed but this is allowed in real life.
- Avadex is no longer on sale.

2.2 Possible Bugs
- If you change the grain value to £100 you loose margin.
- When you try to change the name of the weed list in the Wizard screen it lets you enter it, but doesn't seem to accept it.
- If you change observations of growth stage it isn't carried through to the main screen – it is not listed on the left hand part of the screen and the growth stage doesn't move.
- Black Grass – you get the biggest yield from not treating black grass in any way!
- System defaults to 1st October – this causes all sorts of problems.

3.0 Additional Information

During the course of the training sessions it became apparent that the users wanted a higher degree of information about how the system worked. The questioned where the figures were coming from and how the calculations were being made. They want to know more about this as they feel that they will be better able to trust the outputs if they know how they are being generated.

Additional information required:
- The assumptions behind the model results.
- What variables are in the rotational model and how they are used.
- The assumption behind cost/hectare.
- Will models cope with weather effects on rates?
- Where does the information for yield loss come from in the encyclopaedia? As BG is the same as oilseed rape (5%).
- More basic information on product chemistry; they feel that companies have it but are not releasing it. i.e. strengths and weakness of a chemical. The science of how it works.
- What the last year to be taken into account over the 5 year rotation is.

User Comments:
- Users felt that soil types were important but it was not obvious to them that they were being used.
- Chemicals can kill more weeds than the chemical companies list and they want this to be taken into account. They want to incorporate the common views of farmers and agronomists into the system.
- Users would like to have the options of set aside and fallow for crop choices to be incorporated.

WMSS

User Interview results
Field based trials

October 2004

Section 3 Contents

1. Introduction

This document summarises the results obtained from the user-based activities carried out within the WMSS project between the months of March and October 2004. The purpose of this document is to present a summary of the data from these activities, to present the users views of WMSS and the ArableDS initiative and to outline the areas which were pinpointed as being problematic; any bugs found within the system will also be listed.

The data presented in the rest of this document was obtained from detailed phone based interviews with farmers and consultants who had previously agreed to trial the WMSS software during the 2003/2004 season. A copy of the WMSS software (version 2Ua) was distributed to a group of around 50 users during November, several later releases were provided and distributed. Efforts were made to contact all users on the user database for the interviews described here.

2. Results of user interviews

2.1 Participants

Despite extensive efforts being made to contact all those who agreed to take part in the trials (52), the final number who were interviewed was 18. Some had not had time to use the software in the trial period and others either could not be contacted or were not available to take calls.

The breakdown of participants is as follows: 7 farmers; 9 consultants; 2 lecturers. The table below shows the occupation of all the participants as well as their user number which is used to identify each of the quotations throughout the document.

Table 1: Showing the user number associated with each profession

Occupation	Participant Number
Farmer	2,3,4,5,8,14,17
Agronomist	1,6,9,10,11,12,13,16,18
Lecturer	7,15

2.2 *Perception of WMSS's helpfulness and usefulness*

The participants were asked a number of questions about the helpfulness and usefulness of the WMSS software. The responses to these questions are summarised below.

2.2.1 On a scale of 1-5, (1 being very helpful and 5 being no help at all) how helpful did you find WMSS and why?

Overall helpfulness
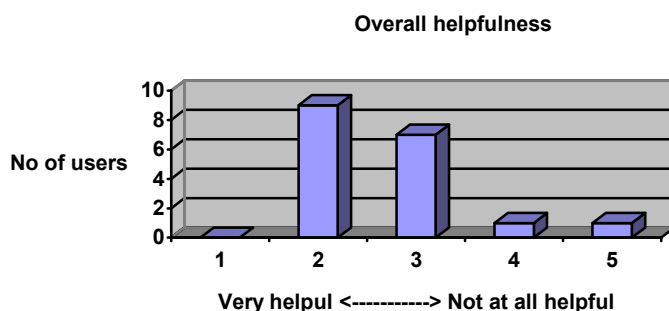
Figure 1: Showing perceived helpfulness (1 = very helpful & 5 = no help at all)

There were a total of 18 responses to this question. The results obtained are shown in figure 1 above.

As can be seen from the results above, half of the users (9/18) felt that WMSS would be useful to them in the future, 39% (7/18) had no strong opinion either way. Only 11% (2/18) felt that it would be little or no help to them.

Some of the comments users made in relation to this question.

Respondents were asked to comment on their responses to this question and these have been summarised below.

Reasons why people felt WMSS would be useful

The main reasons people felt WMSS would be helpful related to the way in which it supported their understanding of weed biology and how it could be used to support the weed management planning process. Detailed comments below:

Tool to understand weed biology

• It was helpful in making him understanding and making him think of weed biology and the population of weeds.(2)
• Reference material excellent. The weed encyclopaedia "best I have ever seen" . (4)
• Used it as a student tool. Very good as a teaching tool. (7)
• Found the actual weed idea really, really helpful to a farmer as they are not sure of life cycles and things like that, very simple to do. So much better than the first disk she had. (18)

Makes complex task easier

• It distils the knowledge and experience he has on weed management into a usable form. (10)

Good planning tool

• Logging weeds in fields and planning is important. The rotational screen looks useful. (6)
• Useful tool early season e.g. setting up scenarios. Excellent as a piece of software. Would use pre season when he has time. (11)
• Rotations screen was a good thing. Just being able to change things so easily and see so quickly and easily the effect that was great.(14)

More robust than previous versions

• Easy to put inputs in.(5)
• Felt this version was easier to use and had less glitches than the other version. He could see what it was telling him. (15)

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Keeps up to date with changing products
- Useful where new chemicals come along as long as it is kept up to date and you can trust the results.(8)

Reasons why people didn't think it was/would be helpful

The main reasons that people didn't think that WMSS would be helpful appear to be their lack of faith or trust in the output it provides and the difficulty they find in using it. Detailed comments listed below:

Ease of use/fit to task
- If he wanted to spray for OSR in peas he would use ?basogeam, the system says to use full rate but he would not use full rate. (3)
- Didn't get on with it very well at the start. Couldn't get it to work properly. (6)
- Would it be possible to have an icon on the desk to go straight to WMSS rather than through Dessac (8)
- Found it difficult to follow. Didn't know what it was telling him. Cultivations confused him.(9)
- The problem is lack of time as it takes a bit of getting used to.(11)
- Some of the ways it looked at things weren't as he would have looked at them. Entering things into it , e.g. if he wanted to sow rape early and BG was one of the weeds when he did suggest treatments it changed the rape to late, he cant sow late as he wont get a crop (14)
- If he got into using it, it would be more useful. He makes mistakes and gets things wrong at the moment as it is not familiar to him yet. (16)
- Far too complicated. Takes too long to put stuff in and difficult to get stuff out. Better to just look it up in a book, the whole thing is so long winded he would just never use it.   Doesn't like the main screen one little bit. (17)
- Downside was it wasn't as straightforward as they had to swap between lots of different areas and screens. (18)
- Couldn't alter non-inversion in the rotational screen. Tried right clicking and nothing happened for the cultivation. *We changed this during the interview and it all now works*. (18)

Belief/trust in system output
- It has to meet his concerns about outputs. It needs ironed out as sometimes it was just recommending cultivations as the only thing in the treatment list. Needs more herbicides. Too narrow a selection at the moment, he wants them all. (6)
- Think the main thing is that he didn't trust what it was telling him to do. As a farmer the weed tends to be the same field on field so he has more knowledge of the weeds than WMSS.(8)
- It doesn't cover all the problems he's had in his fields. He has a lack of trust with what its calculating as the outputs are not what he would have thought. (12)

System stability
- System is unstable at times and often crashes. That's the main problem. (4)

Lack of flexibility
- Only criticism is the lack of range of herbs and lack of flexibility with tank mixes. Should be made as close to real life as possible. (13)

Reasons why people weren't sure either way

Most people who weren't sure either way gave either reasons for using it or for not using it and these have been summarised in the headings above. Others were not sure because they felt they had not had enough time to evaluate it. Specific comments were:

- Depends whether being used as a planning tool or an in the field tool. More useful as a planning tool. Very good theoretical tool but has to take into account all the   idiosyncrasies of an individual farm. (3)

- Hasn't used it as much as he would have liked. (5)

2.2.2 On a scale of 1-5, (1 being very likely and 5 being very unlikely) how likely is it that you would use WMSS in the future?

Likelihood of future use
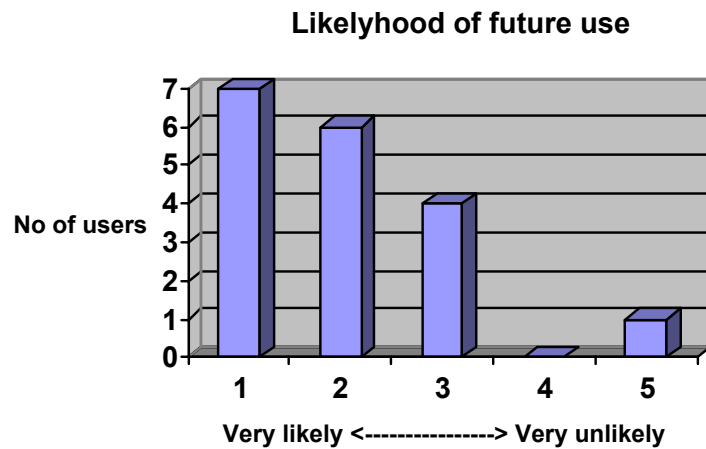
Figure 2: Showing likelihood of future use (1 = very likely & 5 = very unlikely)

There were 18 responses to this question. The results obtained are shown in figure 2 above. The majority of users (72% or 13/18) said they would be likely or very likely to use WMSS in the future. Only one person said that it would be very unlikely that he would use it in the future. 22% (4/18) were undecided as to whether they would use it in the future.

Some of the comments users made in relation to this question
Respondents were asked to comment on their responses to this question. The reasons people gave for believing they would use it in the future related to its value in: supporting a complex decision process; challenging their current way of thinking about weed management; strategic planning of control strategies; teaching; and in dealing with unfamiliar problems. Specific comments are listed below:

Reasons respondents are likely to use it in future
Complexity of decision making makes it valuable
- He likes the rotational screen. Very good to be able to model forward in that kind of environment. Would take issue more often than not to in season results. Rotational plan more difficult to model in your head. I do the spray plan bit every day in my head anyway. (3)
- I think the rotational screens are great. You can run scenarios over a time period. You can look deeper into things with it than you can at the moment. It is easy too look at different plans. You can run lots of different solutions at the same time to see the difference and it is faster than he could do on his own. (4)
- It is so complicated with the different combinations that are available. You will have to use something like this to make sure you don't make mistakes in the future(9)
- The number of products available are reducing and the complexity is increasing so the more tools I have available to me the better.(10)
Challenges your way of thinking
- He would use it a little to see what it threw up. He would be unlikely to put any actual farms in it as he really doesn't have much faith at all in the outputs. (1)
- Thinks it has a value in setting up scenarios and it makes you think. Throws up things you wouldn't have thought about. Would come to same conclusion if a few of us sat down to think about making the same decision. This is just a faster way.(11)
- Thinks it could be very useful to him. If you have an open mind you'll use it (12)

- If product range is improved. Challenges what your mind set is when dealing with a certain situation.(13)

Teaching aid
- Would use if could show it to students as an exercise. Not on farm as its organic.(7)
- Felt that there were features extremely useful in teaching and for students. Especially the rotations to see the effect on populations, and all round integrated approach to weed management. Extremely valuable for those points.(15)

Strategic planning
- It would help him to plan weed control strategies in the winter. Does not see it in the same way as WDM where you would be using it all the time. He would only really use it for strategic planning. (2)
- He would use it as a planning tool rather that something he would actually use to make decisions. I would use it more to create scenarios rather than to make decisions as you have to input too much data. Would give it a 1 if it worked with muddy boots (6)
- It is useful for rotation planning and looking at calculations, it's a graphic way of showing this to farmers (16)
- Just from looking at things in the future with regards to problems has on field at the moment to be able to see what effects things will have in the future. Would use more as a futuristic prediction than on a day to day basis. (18)

Dealing with new problems
- Thinks if you are expanding and taking on new ground and you have a new weed spectrum you would use it for that. When you've been at it all the time on the same ground you know what to do already to control it.(14)

Reasons why respondents wouldn't use it in the future

The reasons people gave for not wanting to use WMSS in the future were either because they felt there were better ways of managing weeds, that it doesn't take data from their crop management system and lack of trust in the output.

Don't need WMSS
- Similar reasons to q1. Weeds don't really change so he knows how to control them without this.(8)
- Same reasons as above….there are better ways of doing what it's doing. Easier to just ask an agronomist or look it up in the book.(17)

Doesn't integrate with CMS
- Not sure it would work with dozens of farms with up to 400 fields. He uses muddy boots and has already entered that data, he wants to link it to that so the info in that is transferred across it would make it much more attractive. Try to sort out compatibility between all systems for arable crops. Not so bad if you have only a couple of farms. Would give it a 1 if it worked with muddy boots.(6)

Lack of confidence in output
- If he could be confident that it was going to work. Doesn't like the fact that it's only for winter wheat. It has to give better results than it gives at the moment.(5)

2.1.3 Would you use WMSS on your own or would you use it with someone else e.g. your client/agronomist to make joint decisions?

A total of 17/18 participants answered this question. The user who did not answer said that he would not use WMSS in the future. The results are shown in figure 3 below.

Who would you use WMSS with?
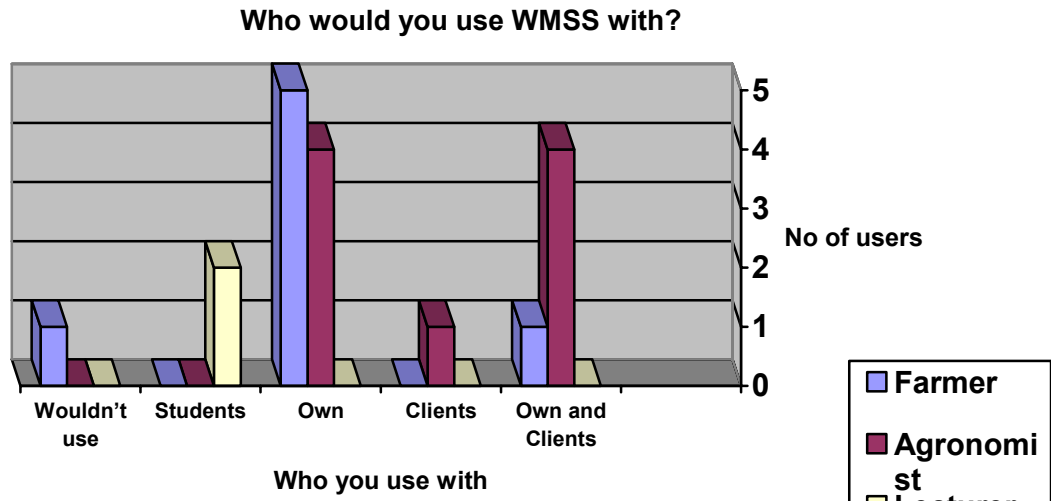
Figure 3: Showing who the users would use WMSS with

As Figure 3 above illustrates 9/17 (53%) users felt that they would only use the system on their own. 7/9 (78%) of these users stated that they currently make all decisions on their own . One person said that he currently made decisions with his agronomist and another person said he made decisions with his father.

Only 1 user (agronomist) said that he would be most inclined to use it with his clients. This user currently makes all decisions by himself and felt that this would be a good way to get the client involved.

Five respondents stated that they would use WMSS both on their own and with their clients, one of these said this would only be true if they needed to illustrate a particularly bad problem. Another of the users stated that they would also like to show it to the people he sells the crops to (farmer).

The lecturers stated that they would like to use it with their students as a teaching aid.

2.3 Past use of DSS

It was felt to be useful to find out what previous experience the respondents had had of using DSS. Questions 3, 4, 5 related to this issue and the results of these are given below. A total of 18 participants answered these questions.

2.3.1 Has a DSS ever been used on the farm/in your business/in your company in the past?

Has a DSS ever been used before
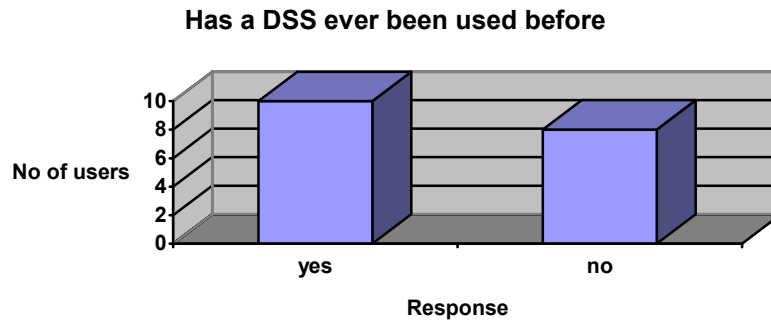
Figure 4:Showing whether a DSS has been used in the past (yes, no)

As Figure 4 above illustrates, just over half (56% or 10/18) users said that they had used a DSS in some capacity in the past. Of those who said yes, seven were agronomists (7/9 agronomists) and three were farmers (3/7 farmers). Neither of the lecturers had used a DSS previously.

2.3.2 What was it/were they?
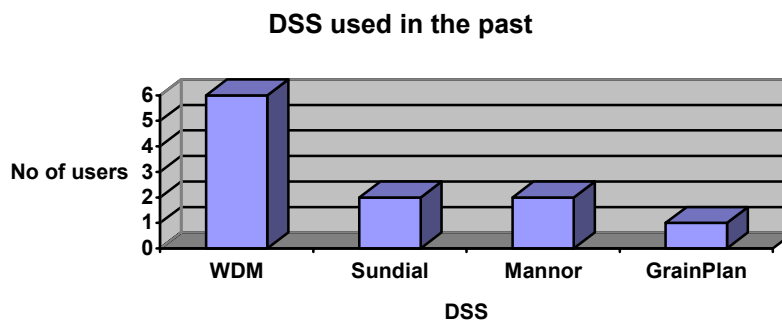
DSS used in the past

Figure 5: Showing the DSS's that have been used in the past (WDM, Sundial, Manner, GrainPlan)

As Figure 5 indicates over half of those who say they had encountered a DSS in the past (6/10) had used WDM. Two users said they had used Sundial in the past and two had used Manner. One user had encountered GrainPlan in the past.

2.3.3 How helpful was it/were they?

The users were then asked to comment on how helpful they felt these decision support systems had been to them. Figure 6 below shows the users perceptions of the helpfulness of these systems.

Helpfulness of DSS

A bar chart titled "Helpfulness of DSS" with y-axis "No of users" (0 to 4) and x-axis "Response". Bars: very helpful = 4, quite helpful = 2, a little help = 3, no help = 0, don't know = 1.
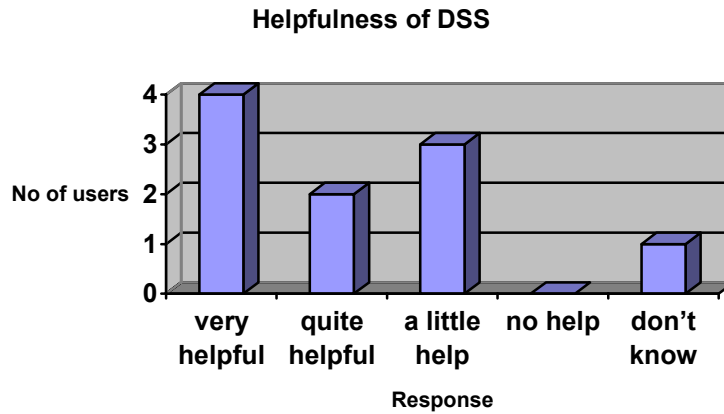
Figure 6: Showing the users perception of the overall helpfulness of previously used DSS

Table 2: Showing the breakdown on the ratings respondents gave each DSS
(1 = very helpful, 5 = no help at all

DSS	1	2	3	4	5	6	Average
WDM	5	1	1	3	2	1	2.6
Sundial	1	3					2
MANNER	2	3					2.5
Grainplan	1						1

None of the users suggested that they found the DSS that they had used in the past of no help at all. One user felt that he could not really comment on it because WDM had been used in his company in the past but it was not primarily used by him. Six out the 10 respondent users found the use of other DSS either very helpful or quite helpful, and three users felt that their use of DSS had been only a little help.

2.4 WMSS specific issues

The next set of questions related specifically to the structure and content of WMSS, the results from these are given below.

2.4.1 What parts of WMSS did you find the most useful and why?

Users were asked to think about the parts of the WMSS system that they found of most use and to give reasons for their choice. A total of 18 users responded to this question. Some of the users gave a multiple response to this question and the responses were sorted into meaningful categories.

The most useful parts of WMSS appear to be the rotational screen (8/18 users) and the encyclopaedia (7/18 users). Other aspects which users valued were: the in-season screen (1/18); ability to see the impact of variables on margin (2/18); suggest treatments function (1/18); and the wizard (1/18).

Comments made by those who valued the rotational screen
- Because he could look at how rotations could effect weed control.(1)
- Made him think more about what he was doing more than he normally would, mainly due to the fact that the results from the system are not necessarily what you would expect them to be. You have to have a lot of courage to use these systems as they will not give you results that you would expect and you need a lot of courage to accept them.(2)
- Because it computes the effect of your fundamental decisions in terms of cultivations which you can't possibly work out for yourself. Rotational and cultural control is becoming more important. (3)
- Looks interesting. Wasn't sure of the results. Couldn't get good control of poppies. Couldn't get good control of cleavers in oil seed rape. Centium needs to be there. Cultivation need more

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than plough and non inversion. You have deep and shallow plough. What does early mid and late mean as it means different things in different crops. Need to know what that means for each crop. (6)
- Timings. Liked the screen as you could see everything clearly. Yield was always off on the rotational screen in his opinion (7)
- Shows weed infestations over 5 years and see how change of crop affected these infestations. Most useful to him (15)
- It gives you a more accurate and pictorial guide. Usually just done in your head but on the computer you have figures and effect on margin so its far more graphic and accurate than they are doing at the moment. (16)
- I can see it would be a benefit. From her point of view she can sit down with farmers and show them what's going to happen and there are also figures in there. Backup to what she's doing on the farm at the moment (18)

Comments made by those who valued the encyclopaedia
- It is so well done. It was so easy to use. Whatever you wanted to find you could get straight to it. Very well illustrated. Would use that feature often.(4)
- It pulls together wide range of technical info into one place. Hard to get that at the moment.(10)
- It is difficult to have that volume of info in your head. Decision making within a field scale is generally easier as you don't need as much information. Useful for rarer things you don't know much about. Most weed decisions he makes are fairly standard that just need limited knowledge to get effective solution. One of the problems is you have to define populations, at field level he feels this is quite difficult as levels vary across the field. At moment you use worst case scenario - not good. Farmer perception has to be taken into account so often he wants things done that may not need done.(11)
- List of chemicals in the encyclopaedia. Easier to see the effects the chemicals have on all the weeds. This is easier to make out than the green book, much faster (14)

- It has a lot of handy info that he can look at, at his leisure and just use when he feels like it. (17)
- The encyclopaedia is so quick and easy to use. (18)

In-season screen
- It gives you an idea of the spray window that you have. Nice to be able to visualise that. You need to be able to use a PDA in the field to log weeds in the field as you go round.(5)

Ability to compare impact of choice on margins
- Finding the most economical treatment. What one gives the biggest margin as he is a grower and that is the most important thing. (8)
- Effect on margin by cultivations and spray choice. It challenges what you normally do. There is science behind the decision whereas at the moment there is no science behind his decisions, he just does what he feels (13)

Suggest treatments
- Makes you think about what you're doing, makes you reappraise what you're doing. It has to be more comprehensive. There are a limited no of products. Wants to see all the products in there (12)

Wizard (1)
- A lot of it was click on and click off. It was easy to use. (9)

2.4.2 What parts of WMSS did you find the least useful and why?
A total of 18 users answered this question. There were quite a range of responses but no single part of the system excited a lot of comment, the most frequently cited aspects of WMSS which users found least useful were the In-season screen (3/18), the rotational screen (2/18); system output (2/18) and the suggest treatments function (2/18); all other parts of the system were mentioned by only single users. The reasons the users gave for selecting these components are summarised below under appropriate headings.

Output

- The bits he found least useful were when they gave out silly results, like he changed the weed list and this had no effect on yield. The system recommended that he put Duplosan on just about everything which was something that he wouldn't do. He could not get control over sensitive poppy in the rotational screen (this is because he didn't realise that it is seed bank and not plants that are being shown) (1)
- <Rotational screen output> The user wouldn't be interested in margins on this page. Felt that it didn't really give accurate results. (5)

In Season Screen

- It is a function that he is quite happy with <*doing the way he currently does it*>. He currently does it and knows he can do it. Feels he maybe should give it a little more time to look at sequences. Would be useful to look at sequences for sprays for hard to kill weeds like BG. (3)
- It was difficult to use and not very clear. There were too many icons and the screen seemed to have too much information on it at first glance. This is the part he would use the least. (4)
- Found it confusing, didn't know where he was to make proper use of it. He doesn't know how we could make it better. (17)

Rotational

- The user wouldn't be interested in margins on this page. (5)
- He hasn't done much with it. He didn't agree with some of the results, but this is probably due to lack of familiarity with the system. (13)

Suggest treatments

- It didn't suggest BG control. He knows what he wants to use and he would rather put that in to see what the results were.(6)
- It was most confusing and the least helpful aspect of the system for him. It took 3 or 4 minutes to optimise. Wasn't really clear what he was getting. Couldn't tell which treatment was which on the in season screen. The tractor does not say what was being done. Didn't want to move them as he didn't know which was which.(15)

Cultivations

- Thought this was not an important aspect. Cultivations are currently discussed but this is not always what the farmer does. Sometimes you just have to plough. (9)

Encyclopaedia

- It didn't really make him think at all. (2)

Decision Support

- This is possibly because he has to get used to using it. Found difficulty navigating the decision process e.g. adding observations. Results didn't feature what he thought they would. (10)

Yield loss bars

- It may be useful when persuading a farmer to do something, not really useful though. Nice that its there though. (11)

Spray Nozzle selector

- He has never got into it with his clients before, so he can't see himself doing it in the future. Not part of his job to a great extent. (12)

Add Observations

- It was quite limited. Found the ranges for densities and cover hard to fit into what he was thinking about. Hard to change what you actually see in the field into numbers. (14)

Chemical list

- It is not as up to date with what there is available at the moment and there are not enough chemicals in it (18)

2.4.3 On a scale of 1-5, 1 being very useful and 5 being not at all useful, how useful did you find the suggest treatments screen and why?

Figure 7: Showing the usefulness of the suggest treatments screen (1 = very useful & 5 = not at all useful)

A total of 18 participants answered this question. Figure 7 above shows how useful the users felt the suggest treatments screen was on a scale of 1 to 5. Just under half of the respondents felt that the suggest treatments screen was either useful or very useful (7/18 or 39%) and a similar number were undecided (8/18 or 44%). Three people (17%) felt that the screen was either not useful or not at all useful.

Some of the comments users made in relation to this question.
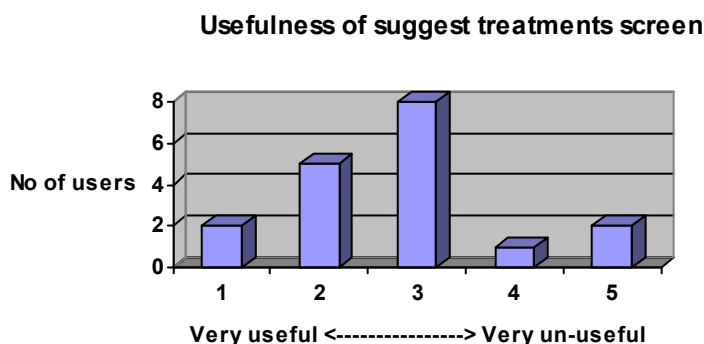
Usefulness of suggest treatments screen

Very useful <----------------> Very un-useful

Respondents were asked to comment on their responses to this question and these have been summarised below.

Positive comments

The most frequent positive comments related to the way that the output from the suggest treatments could be used as a way to enhance the users own decision making i.e. by suggesting things that they hadn't thought of or by kick-starting the thinking process. Specific comments are listed below:

It made you think
- Thought it gave valuable information that made you think about what you were doing as it was different than what you would expect. (2)
- Found it interesting. May suggest something you hadn't thought of before. Interesting more than useful. It gives too many options. (3)
- Use to be an agronomist but has lost touch so she found it useful. She had her ideas and then looked through to see what it came up with. (7)

Range of options given
- It gave a broad range of options to treat the problem. (8)
- Self evident. It does what you want it to do. Feels it may come up with too many options. From a practical point of view how many do you really need. (11)

User friendliness
- I thought the screen was ok (1)
- Found it ok. It was quite clear. Because it was ok he can't really remember much about it (4)

Gives an excellent starting point
- It gives you an excellent starting point for what you're planning. (12)

Liked the gross margin feature
- I like the fact that you can see you are changing gross margin so quite good. (14)

Negative comments

There were quite a number of negative comments in relation to the Suggest Treatments screen. These mostly concerned the users unhappiness with the way that chemicals were used within the system (too few) and problems with running it. Other comments suggested a lack of trust in the model output. Specific comments are listed below:

Product/cultivation related comments

- Need more chemicals. (3)
- Not useful as its dealing with a very limited database. Would like to suggest the products he wants to work with. He would give it a 2 or 1 if it could be improved in that way (6)
- It didn't take into consideration reduced rated. It was only full rates you could use. This would put him off using it. (9)
- Would like to see as many chemicals as possible in the list. Defaults will do, don't need all IPUs. (11)
- He options are fairly narrow in terms of tank mixes and product choice. In reality he has a massive tool kit to use but only a small portion of that is available here. (13)
- Needs to have as many pesticide options as possible. Full range out there should be in here. There are cheaper older products out there. It is very limited at the moment, though this wouldn't stop him using it but would be more useful with more. (16)
- Wants an option at start of program you should have a tick box where you can say don't include plough. (17)

Problems getting it to work

- Didn't look at it as a solution mainly due to the treatments that came up. He would mainly just use this for more difficult decisions to see what came up. Not getting anything useful out of it at the moment (1)
- Every time he's tried to use it he didn't get any results.(5)
- Not obvious where he should go or what he should do. Doesn't say what the process is. A wizard would be good (10)
- Very slow on his machine so it was frustrating. It was fairly clear when it actually suggested them. His computer is just too slow and not really up to the challenge of running it. Could have been more helpful. He could see there were differences in yield, because the cultivations came first that's all he could see. Should highlight the differences between them easily. Didn't know to click on double bar. Doesn't want cultivations first. (15)
- It didn't work for him. The only thing it suggested was Mouldbough plough. Would have given it a 4 if it had worked. *Note: went over the process with the user while on the phone and it suggested feasible treatments for the first time.* (17)

Lack of trust/belief in outcomes

- Didn't trust everything it told him to do. (8)
- Doesn't really change your yield as in bring it up. Found it hard to have an impact on the yield. Didn't seem to go up the more money you spent. (14)
- When shown at HGCA thought it was BG oriented and that affected the financial figures as you had to spend more money to control BG. Could be the examples he was given as they all had BG so that's maybe why he feels it. (16)

Output too general

- Didn't find it very useful at all. Because it is generally the case that she has certain things that she would do for each individual farm. It just gives you an overview rather than a specific answer. There are lots of other things that influence her decisions for each farm. (18)

2.4.4 What do you think the suggest treatments screen is telling you?

In order to clarify the comments on the usefulness of the Suggest Treatments screen participants were also asked what they felt the screen was telling them. Most people saw the output as a set of suggestions they could use or ignore as they chose, a few saw it as more of a definite recommendation. There were

also some comments about the function of the elements of the screen design. The comments are summarised below under appropriate headings.

Looked at it as an option rather than a solution
- I thought it was making suggestions of what I could possibly use. Never thought it was telling me what I should be doing, more what I could be doing. (2)
- What you might do to overcome problems. It is an idea rather than a, you should do this (3)
- It was suggesting treatments that you could use. Interpreted it more as a suggestion than a, this is what I should do. Used it as a suggestion then went into in season to see kill rate on the weeds. He used it all as a package rather than just going on just that one screen. He also looked at other chemicals. You should use your own judgement when using it. (4)
- They look like sensible suggestions. Knew triangles were timing. (5)
- Was confused by the boxes, couldn't see how it fitted in. It only concentrated on cleavers. Cultivations were first in the list, wants to be able to look at them separately as you want to compare them all. Cultivations are not the most important thing. Wants cultivations separated out as once there done there done. (6)

- It was giving ideas on treatments. She had her own idea and it gave her other options. (7)
- It gave a number of options for solving the problem. You can then modify the treatments. It shows the relative yield and margin. He thought it was just a suggestion that he could work on. Never looked at is as a black and while thing (12)
- It gave the option of a number of treatments. You could decide whether to choose one with a large range of variability and hope it is in the top part of the range or you can chose one with less range and a smaller top margin as you know it wont go below a certain level. (13)
- It showed what treatment will give you the best control. Hasn't used it enough though. Would never just let the computer make the decision, he would always look at it as options rather than a, you must do this (16)
- Giving her various options with regards to the cultivations she had done and gave the possible yield or margins she would get. (18)

The system showed them the best possible treatment plan
- Give the best cultural and chemical way for control. It set him thinking (8)
- Most cost effective treatment for those weeds. Thought the system tried to tell him best thing to do. (9)
- It showed what the best economic treatments were. Gave a range of options. List of best to less good. Worked on economics. Shouldn't put too many pounds at the side as you have to be careful as it makes people think this is the best. Control of the weed is a valuable thing. (11)

Provided difference in various chemical uses
- A variety of treatments based on weed spectrum entered, demonstrated predicted yield, not the definite yield. Telling him the difference in the various chemical uses. (15)

Misc. comments
- It gives option of fixing dates or not. There are 2 parts of decision, chemical and cultivation. I didn't like the results and would only consider 2 of the 15 suggested. Unclear whether plough is a recommendation or a default. Wants to know how much it will cost. Cost per hectare is what he wants to see. (10)
- It was ok. Some of the suggestions didn't make sense to him. (14)
- Nothing to work with so he couldn't really comment as it just said plough as the only option all the time. (17)

2.4.5 Do you think that this would be made clearer if we changed the name from suggest treatments to something that made it clear that it was more of a prompt than a proposition?

As it was felt that there might be some confusion over the nature of the Suggest Treatments screen respondents were asked if they felt the name should be changed. The responses were mixed. A total of 17 users answered this question. Eight out of 17 respondents felt that changing the name would not

make the suggest treatments screen any clearer, five felt that it would and four did not know. Some of the comments are shown below, these also reflect the differences in opinion.

Yes the name should be changed
- Yes the name should be changed as it is very misleading. It currently suggests that this is the treatment you should be going for rather than just an option. (1)
- It says that if you do this and if that's not what you were thinking then your wrong. (14)

No, it does not need to be changed
- I didn't find the name misleading. (2)
- Suggest treatment is fine as it is a suggestion rather than prescription. It doesn't say 'do this'. It will be hard to find a better word. (3)
- I took it as possible options. (7)
- Depends how you look at the system. Some people may think it gives a blueprint but he has never thought of it like that. He sees it as mere suggestions that he often disagrees with. (13)
- Feels the name is fine. I think growers will use it to give them a series of choices to control these weeds. (15)

Miscellaneous
- He was confused by this window. Didn't know how to use the 4 windows. Didn't find name misleading. Final window should say spray results. (5)
- She found cultivations very good. (7)
- It is difficult as we all believe software is there to give us answers. It is our perception that is at fault. (11)
- When you say suggest treatments people would think it is an alternative to what they are currently doing. Difficult to give it a name as it is really just an indicator. (18)

2.4.6 What do you think the Suggest Treatments option should be called?

Some of the possible suggestions that users gave as an alternative were:
- Possible Options(7)
- Treatment Plan(8)
- Ideas List(11)
- Legally Recommended Options(14)
- Treatment Options(16)

2.4.7 Other comments relating to the Suggest Treatments screen
A number of other comments were made about the Suggest Treatments screen which weren't covered under the question headings above. These are listed below.
Changes requested
- You get cultivations first rather than sprays. Want to see sprays first then the cultivations as the sprays are the most important. Would like to be able to see all spray plans together to compare them at a glance. (5)
- As an agronomist there are certain chemicals you don't want to use for certain reasons. Sequencing of herbicides would be really useful. Have something flash up to alert the user about sequencing restrictions. Also following crops e.g what you cant plant due to restrictions with last years applications(6)
- Have a pick list of possible treatments that might be used. 6 or 8 standard treatments you'd consider, he wants to be able to choose them. He would say I want to use A, B and C and the system should then say well that will leave these weeds behind. (10)

2.4.8 When you first open up WMSS would you like to go straight to the rotational or the in-season screen? Why?

Figure 8: Users view on which of the main screens should be shown as default

Respondents were asked which of the two main screens they would prefer to see when they opened up WMSS. As Figure 8 shows there was no significant difference between the number of people who would prefer the rotational screen to be viewed first (8/18 or 44%) and those who would prefer the in-season screen to open first (9/18 or 50%). The user who indicated that he would like neither screen to be the first screen asked that the system take you to a screen where you can choose a field and then move onto the in-season screen.

Table 3: showing breakdown of screen preference by occupation

	Rotational	In-Season	Other
Agronomist	5	4	0
Farmer	3	3	1
Lecturer	0	2	0

The preference for screen does not appear to be occupation specific as an almost equal split of farmers and agronomists chose each screen (Table 3).

The reasons for the choices the users made are given in their comments below. Most people who opted for the in-season screen suggested that it would be the one most frequently used. Those who opted for the rotational screen felt that it was the logical starting point or the screen they found most useful or interesting.

Which screen should you see first?
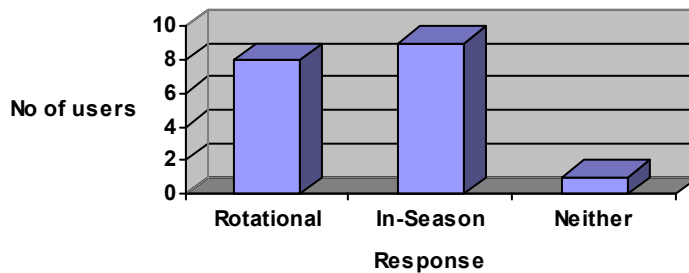
Reasons for choosing the in-season screen
- Easy to swap between screens so it doesn't make much difference. More logical to go to the in season screen. Its an easy program to navigate so it doesn't matter where you start off. (4)
- Thinks the current information is on the in season screen. You use this to make spray decisions not rotational decisions. You only use the rotational once a year. (5)
- You are more likely to visit the in season as you will use it more often. Rotational is long term planning so you would use it less often. Not really important as you can change easily between the two. (6)
- She looked at the in season screen. Found it more interesting. (7)
- It's the one that you would use most often. Every 4 of in season screen he would use rotational once(8)
- Not really sure, he thinks he's just used to it this way. (12)
- Most of the time your looking at it you will be looking at the in season screen. There are not too many steps change view so it doesn't really matter. (13)
- If using it for real he would like to see where he is today. (15)
- Initially you want to put in what you have on a field by field report. You look at fields specifically for the problems. If you looked art the rotational screen first you can't be as specific as you haven't set up or looked at all your weed lists yet. (18)

Reasons for choosing the rotational screen
- It would be easier to start with as it is not so complicated and really would be a better aim for the whole project. The project is biting of more than it can chew at the moment with the application rates for the in-season as full rates are very rarely used. Although they are being used more often as full rates than a few years ago because weeds are becoming harder to control. (1)
- It is a reminder of where you are exactly. It is in the wrong order as you forget to go and look at it. At the moment it is in the wrong order as you don't
remember the rotational side. It would be useful if the system made you look at it by making it the first screen. (2)
- That's where the farmer would start. (9)
- Didn't know to double click. Didn't know what that was telling him. Oats are not an option. This is what sets the long term scheme of what he's trying to achieve. (10)
- That's where you should start as it is where you start in real life. Used to look at different scenarios. (11)
- He was more interested in that screen. He was only playing with it and found he was more interested in the rotational. That's where he wanted to start playing. He would look at the rotations first before the in season (14)
- He would use the rotational screen more. He can see a benefit using it with clients. Sit them in front of it to say if we did this we would get that so we have to do this too. (16)
- The in season screen should look like the rotational screen or at least very similar. The rotational screen would be more use to him than the in-season screen. He wouldn't use the in-season screen as he feels its co complicated. (17)

2.4.9 What do you think the rotational screen is trying to tell you?

Participants were asked to give their views on the purpose of the rotational screen in order to determine the success or otherwise of the screen design. Most of the respondents took the view that the screen showed them the effect of various strategies on weed numbers over time. None picked up that it described the seed bank in the upper layers of soil. Some respondents felt that it was more concerned with presenting margin over time. Comments are summarised below under appropriate headings.

Weed population over time
- How weeds will develop in the future. (1)
- It reminds you what the consequences of different approaches to management are. Puts the whole DS thing into context. (2)
- The consequences of the more fundamental policies on cultivation. He looked at it as the risk. (3)
- Longer term view on weed population. I looked at ways to get the colour to go down as the main thing; I just paid attention to weeds. I didn't notice margin at all till you mentioned it. (4)
- It appears to try to show how your weed burden will increase with sprays and cultivations that you are using. (5)
- What the cropping, cultivation, etc are. What implication they have on weeds in terms of numbers. (6)
- You can select crops and cultivations which have an effect on weed control. It is very useful. More useful than the in season screen. (9)
- Which crops will give you more problems with weeds? Which crops youd struggle to get good control over (10)
- Showed you what the effect of the rotation would be on the population of the weeds. (11)
- Risk of certain rotations and the cultivations etc on the weed population. (14)
- The effect of different crops in the rotation on the weeds in the field. (15)
- It shows the effect on the weed populations of the cropping and treatment and sowing date over multiple years. (16)
- Chance to see how you can alter things. You can try to get the best out of the system and the best course of action to take. (18)

Gross margin over time
- It was the gross margin over a number of years. (8)
- Gross margin. (9)
- Wasn't sure to be honest. (12)
- What the potential margin is over a period of years, what the potential weed problems are so whether you're going to run into a problem with a particular weed in a particular year. (13)

2.4.10 User's opinions of the coloured bars in the rotational screen

In answering the previous question many users commented specifically on the meaning of the coloured bars in showing weed seed numbers. Many felt that they represented number of weeds and not seed levels, a number also felt that the colours were not sufficiently different from one another, several people were unsure what the colours meant. Detailed comments are listed below:

- Found the colours confusing, wasn't too sure what they meant. Thought it was weeds in the crop and not seed bank(1)
- The coloured bars represented the number of weeds. (2)
- I thought it represented the risk. I found it hard to distinguish between the colours as they were all a bit naff, except the red, there needs to be more of a contrast between them. You could set your own key colours for the rotational screen. (3)
- Thought coloured bars were the lighter the colour the less the weed problem. He thought it was actually plants rather than seed bank levels. (4)
- Thinks it is population of weeds to expect in that year according to what you have done. (5)
- I knew what the colour coding was but found it confusing. I thought it showed the level of the weed problem in the crop. I didn't know it was the seed bed. (6)
- I thought the coloured bars showed the effect each of the weeds had on the yield. (7)
- The colours were relating to the difference in the gross margin and whether it was improving or not. (8)
- Bottom part of screen showed the severity of the weeds in the crops. I think this is a useful part of the screen. (10)
- I wasn't sure what the colours represented. (12)
- I wasn't totally sure what this part of the screen was telling me. (13)
- It showed the weed burden. (14)
- I thought the bottom bit represented how many of each species would be present in the crop that I was growing. It could have been clearer, I liked the visual representation but felt it needed a key to know what the colours related to. (15)

Miscellaneous comments on rotational screen
- You need to know what early middle and late means, is it related to the crop itself? (6)
- Margin is interesting too some extent, though I want to be able to put in the cost of a cultivation myself as it varies from place to place. (6)
- Liked the effect cultivations had on this screen. Like the screen even though I was misreading it. (7)
- Need an option for maze or veg (non cereal break crop). (10)
- Can't see what figures it is using in the calculations, so he felt he had little control over what it was doing. (12)
- You could easily see what caused the problems. (14)
- It's a super screen, I like it a lot. (17)
- The screen was easy to read and I liked the way you could change things so easily. (18)

2.4.11 On a scale of 1-5, 1 being really like and 5 being really dislike, How much do you like the layout of the rotational screen? Why?

Figure 9: Showing how much the users liked the layout of the Rotational screen

As Figure 9 shows 15 of the 18 respondents said that they either liked or really liked the layout of the rotational screen. One user neither liked nor disliked the screen and two users disliked the screen. The reasons they gave for liking the screen generally related to the ease with which they could use and interpret it, the reasons for disliking it related to the use of colour and it not being easy to see how to change things. Detailed comments are given below:

Positive comments

It is easy to use
- I found it easier to read and understand than the in-season screen. (2)
- Found the rotational fairly easy to understand. No problems with it. (3)
- I found it easier to use than the in season screen. It is easy to use as you can change rotations so easily. (4)
- I liked the way it is easy to change the crop and cultivation etc. (5)
- It looked easier to read than the in-season screen as it is not as cluttered. (9)
- It is reasonably easy to understand and visually ok. (11)
- It was easier to read than the in-season screen as you can't see the whole time line in the in season without moving it, so it's harder to keep track of what is happening. (14)
- It is easy to look at. Easier to interpret. (18)

The information is clear and simple
- Nice and clear and simple apart from the fact that she was misreading it as she thought it meant actual plants. (7)
- Clear colours and a very visual picture. Mislead as he thought it was gross margin(8)
- It's pretty clear. (12)
- All the information is just there in front of you and very useful. (17)
- It is very simple and all in front of you (18)

How much do you like the layout of the rotational screen?
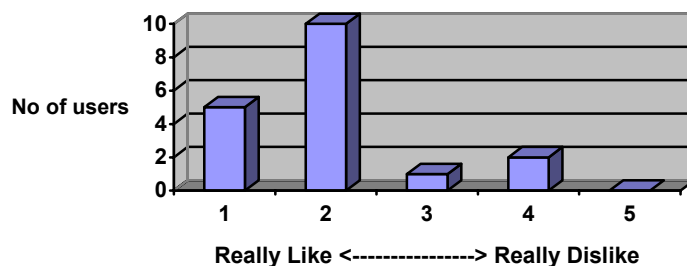
Liked the colour usage
- The colour coding was good. (4)
- Liked the use of colour especially when changing crop. (6)

It follows the natural process I would follow if not using this system
- It is the same layout I would naturally choose to organise a rotation. If he was doing it for a farmer this is how he would naturally plan it out on paper, a computer or on a wall chart. Shows you what you need to see. The margin is also important. (10)

It is fine the way it is
- It seemed ok to him. (2)
- Scenarios could be run very quickly gave a nice graphical representation. (4)
- Can't see any major improvements could be made to it. (6)
- I liked it, it all seems to be there in one screen, and you don't have to scroll from one screen to another the way you do in the in-season screen. (13)
- When you design anything like this you can't keep everyone happy. Drop down lists with the calendar dates are good. Over all it is well laid out and fairly graphic. It doesn't take

How clearly does the Rotational screen show the seed bank level in different years ?

Really Clear <-----------> Really Unclear
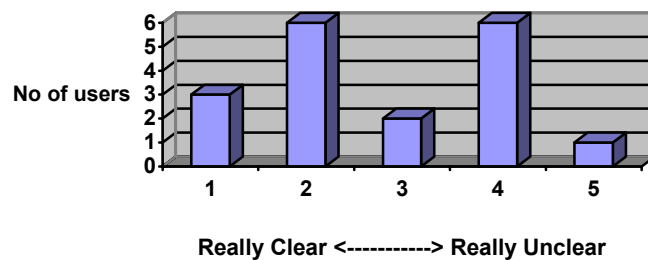
that long to understand. (16)

Negative comments

Disliked the colour usage
- It's a bit grey. (1)
- Not enough bands of colour. It is too vague at the moment. You need a bigger range of colours. (5)
- Lack of clarity with colours. (15)

Not obvious how to change rotations
- Not obvious how you can change the rotations. Didn't know to right click. (1)

2.4.12 On a scale of 1-5, 1 being very clear and 5 being very unclear How clearly does the rotational screen show you the level of your seed bank in different years? Comments?

Figure 10: Showing how clearly the Rotational screen illustrates the level of the seed bank in different years.

As figure 10 shows opinion was divided on how well the rotational screen illustrates the level of the seedbank in different years. User comments suggest that while some people were happy with the colours used quite a high percentage were unsure what the colours represented i.e. seed bank and need more support to interpret the screen.
Detailed comments are shown below under appropriate headings.

Positive comments

The use of colour helped
- It's fairly clear as you can tell how bad it is from the colour.(2)
- Visually it is good. Thought there were enough colour categories. (11)

- Intuitively knew red would be lots. (15)

It was fairly clear
- There are too many unknowns to make it any more accurate than it is. If you use it you have to accept that it is broad brush. He was happy with the fact that it was not totally accurate in numbers. You can get problems when trying to be too accurate as you don't have an exact number at the start in the first year.(4)
- It was fairly clear(13)
- The coloured boxes were very clear. No problems with it at all. (14)

Negative comments

Unsure what the colours represented
- He wasn't sure what the colours were and thought it was showing the plants rather than seed bed. (1)
- 2 of the reds look far too similar to him. Deeper red or purple at the top end would be better. (2)
- Not very clear would like to be able to choose own colours. (3)
- You only have 3 colours. Needs more division in the scale to illustrate wider range of seed numbers. (5)
- Colours need to be differentiated a little bit, with some text.(6)
- He needs to know what the range of the colour scale is, presumes red is high but did not know what low was. Wants to know if it is increasing or decreasing. (10)
- Not totally clear how many coloured bands you have, you need a scale to show how many bands there are and to indicate the full range of the colours. (12)
- Wasn't sure what the colours meant. A scale on the bottom would be better so that you could see what the colours meant. (17)

Didn't know it was showing the seed bank
- Didn't know what that was. You need to say that it is seed bed. (6)
- Wasn't sure what it was showing. Not clear at all till she was told what it meant. So it has to say seed bank so you know. (7)
- Didn't know what it was. Thought it was showing the gross margin. (8)
- Didn't understand it as he thought it was the control of the weeds. (9)

Wants more information on the science behind it
- The system does not really tell you what the coloured bands relate to in terms of numbers. Would be nice to know what they relate to in terms of numbers, e.g. high is 5 BG seeds per gram. This information must be somewhere in the system in order to calculate this in the first place. It would be nice to understand the scientific facts behind the thing as I am used to referring to the science at the moment when I do it manually. (13)

You don't automatically look at the seed bank part of the screen
- You have a lot of other information on there. The seed bank level is not what you immediately look at as it's at the bottom of the screen. Not a big problem. Depends on how much red is down there, if there is a lot of red then you would look at that area a lot more than if there was no red. (16)

2.4.13 At the moment the rotational screen optimises solely on the basis of margin. Would you like to have the option to optimise on different things other than margin? And if so what would they be?

Figure 11: Showing whether users would like to optimise on something other than margin.

Of the 18 users who answered this question half said that they would like to be able to optimise on something other than margin, and half said they would not. Most suggestions were for targeting or ignoring seed bank of specific weeds; and margin. Detailed comments are shown below.

Reduce/keep in specific weeds
- Would like to be able to select certain weeds that you could have a certain level of as all farmers are different. Some don't mind a couple of poppies poking through if it means they can miss out a spray, whereas others are willing to spend a lot of money to kill everything. It doesn't take anything else into account such as having potatoes in encourages PCN and then you have that if you go back to potatoes. The system should take other factors into account. (1)
- Would like to be able to keep a certain population of wild oats in, perhaps 1 per square metre or a lot less. (5)
- If it was possible to optimise on reducing seed bank on BG or Italian Rye Grass. (13)
- May like to say you didn't want to completely eradicate a certain weed. (15)
- Future support payments and environmental schemes would make keeping some weeds beneficial so that would be good. (16)

Margin
- Margin will be difficult to deal with over the next few years as prices change, so you have to look at it flexibly. Margin is what drives job so the most important factor. No use if you let weeds get out of control though. (13)
- Margin mainly. If you could tell it you're going fully to min till or sticking mainly to the plough. If you could give it a list of options rather than the full list being available to it. (14)
- Margin is the main thing with growers though. (15)

Misc
- Fertiliser is not in here, I would like to see that included. (5)
- Look at reducing weed seed bank. (7)
- Useful option to optimise on different things. Sowing dates could be fixed. Sometimes you have to sow early as you can't put everything in at once. (16)
- Helpful if you could add in a yield so you could optimise on that. Cost to produce a ton would

Would you like to be able to optimise on something other than margin?
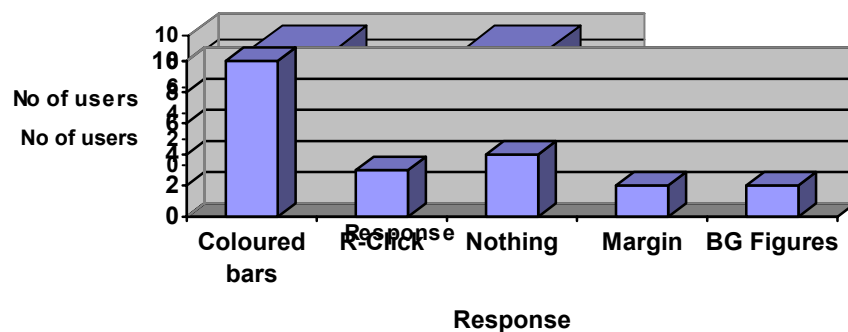
be useful if it was incorporated somewhere. (17)

2.4.14 What areas of the rotational screen are the least clear? How could they be improved?

Figure 12: Showing the areas users found the least clear in the Rotational Screen.

A total of 18 users responded to this question, and figure 12 illustrates 10/18 (56%) of the users had a problem with the coloured bars at the bottom of the screen. These users did not know what the colours were representing, or exactly what that area of the screen was trying to tell them. They were under the impression that it represented the actual weeds present in the field.

Three of the users (17%) had trouble realising that you have to right click to make changes in the top half of the screen. One of them suggested that a prompt appear if you right click on the box to tell you to right click.

Two of the users (11%) had a problem with the margin. One said that he did not even see the margin bar, he had no recollection of seeing it. The other user was unsure what average margin over rotation meant.

Two of the users (11%) felt that they wanted to have more access to the figures that were being used in the calculations. They wanted to have some sort of button that you could click on to go deeper into the system.

Four of the users (22%) felt that there was nothing wrong with the screen at all.

2.4 Questions relating to ArableDSS

The next set of questions were posed in order to find out how the users felt about the dissemination of WMSS and the various options available. The first in these series asked specifically about the ArableDS initiative.

2.4.15 Have you heard of ArableDS?

Have you heard of ArableDS?
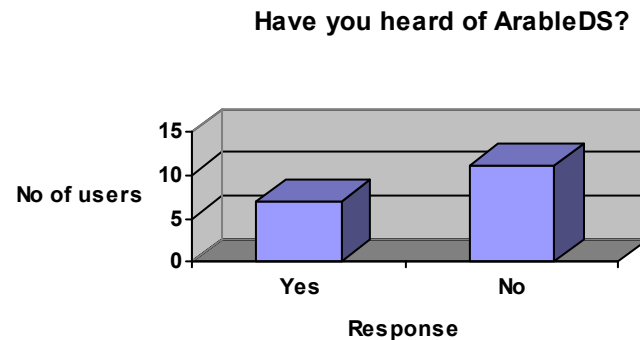
Figure 13: Showing whether participants had heard of ArableDS.

Figure 13 above shows that 7 of the users had previously heard of ArableDS, 11 had never heard of it before. Of the 7 users who had heard of it before 3 were agronomists, 3 were farmers and 1 was a lecturer. 4 of the users who had heard of it before were WDM users.

2.4.16 What do you think of the ArableDS idea?

The ArableDS concept was explained to those participants who hadn't heard of it and they were all then asked what they thought of the idea. The majority (17/18 or 94%) of those asked said they felt that in principle it was a good idea. There were some concernes expressed about cost, some users commenting that the cost-benefits would have to be demonstrated. Two of the participants felt that the training should be tied in with Basis or NROSO (national register of spray operators) points. Two others felt that the social aspect of the training was also valuable to them. A variety of other views were expressed by individuals, detailed comments are provided below.

General view
- It's a good idea. He feels that Arable DS is a positive step. (1)
- It is a useful idea. (2)
- Good idea. (3)
- Very good idea (4)
- It is useful as it is a 2 way thing. He can feed back information too (6)
- I have just heard the name. Thinks it's a good idea that might make a difference with progressive farmers (7)
- Thinks it's a good idea. Anything that makes business more efficient is good. (8)
- Providing there is not a lot of travelling (9)
- The idea is good. Not sure if he would use it. Depends if its any good or not (10)
- Good idea. Heard there was something like this happening. (11)
- He thinks it's a good idea. Need support to get the full value out of it. (12)
- It depends on the cost element against potential benefits. (13)
- It's good in some situations. (14)
- Good idea. Useful in getting people to use the systems properly. (15)

- Sounds like a good idea. Was given a leaflet on it at HGCA meeting. It's the way we have to go as we have to justify things more and more. (16)
- Sounds like a good idea. (17)
- Good idea because everything happening with changes in agriculture. Cant just do things any more because its what you done in the past with all the legislation. (18)

Would like it tied in with training points
- Would like to be able to get points for NROSO from it too as this is probably of more value to practical farmers like himself (1)
- Basis points are a good way to get people to come to short courses. Get people signed up then they are easy to contact and get feedback from. (15)

Enjoyed social aspects of training
- Helpful to be able to listen to other people's views and opinions at the meetings they have during the year. (2)
- Good opportunity to mix with other farmers and agronomists too. (18)

Views on cost
- Happy to pay the subscription fee, has joined already. (2)
- Modelling relies on good up to date data, costly to keep the data updated. Cost may make it too expensive to join unless there are subsidies due to the cost of keeping the data up to date. (3)
- Depends how much it is. It's good for the current price. (5)
- It depends on the cost element against potential benefits. (13)
- Would rather be trained for free and pay for the program as he feels that he would require a great deal of training to be able to use it. When told it was a 1 off fee though he said that this would be ok as long as you didn't have to pay for each training session (17)

Other views
- Feels he needs to get more enthusiastic about the software as he used it less this year than last. (1)
- Costs too much money to develop. He is on the HGCA development committee. (3)
- Uptake could be limited if it gets too complicated. If something gets too big the whole thing becomes too much of an effort to use. (3)
- You have to be able to choose the ones that you want rather than having to take the full package. (6)
- WMSS has more potential than WDM. (6)
- It would be great if you could link it in with muddy boots. (6)
- Good if all info is pulled together. Spends a lot of time on other training and trials at the moment. DSS depend on manufacturers labels, they just want to know if its going to do the job at the end of the day. They are there to make a profit so don't want to be tied into legalities of the dose the manufacturers tell them to use. Farmers may need this to stay within legal mixes. Due to traceability they have to keep up with legalities a lot more (14)
- Getting people to use WMSS for half a day is needed so they can see its full potential as it is very multi faceted (15)
- Public and environmental pressure causing this. (16)

2.4.17 Would you join ArableDS?

Would you join ArableDS?
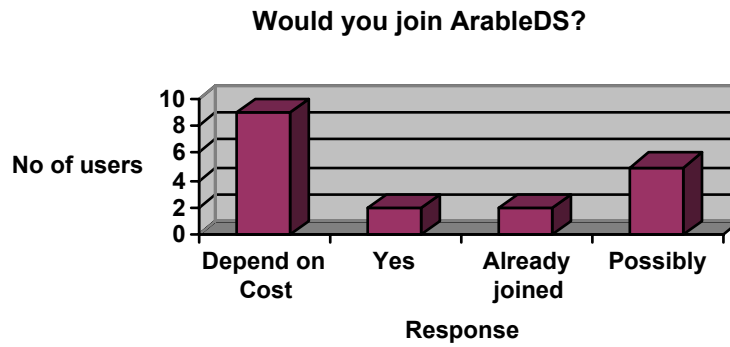
Figure 14: Showing whether users would join ArableDS.

Particpants were then asked if, based on the description they would consider joining Arable DS. Figure 14 above shows the users response when being asked if they would join ArableDS. Nine users (50%) said that they would be interested in joining but ultimately it would depend on price. Two of the users (11%) said yes they would definitely join. Two users (11%) have already joined and five users said that they would possibly join. No users said that they would definitely not join.

It is interesting to note that eleven of these users had never heard of ArableDS, and after hearing a short description of what it was, most were willing to at least consider joining.

It is also an interesting point that eight (44%) of the users questioned have never previously used any decision support system before.

Table 4: Interest in joining ArableDS by occupation

Occupation	Yes	Already Joined	Consider	Cost
Agronomist	0	1	1	7
Farmer	2	1	3	1
Lecturer	0	0	1	1

As table 4 above shows the agronomist respondents were more concerned about the costs of the system than the farmer groups, seven out of nine agronomists said they would be interested in joining but it would depend on price (78%) in comparison to one of the seven farmers (14%).

2.4.18 What do you think would be a reasonable price to pay for a yearly subscription to either WMSS or WDM?

What would be a resonable price to pay?
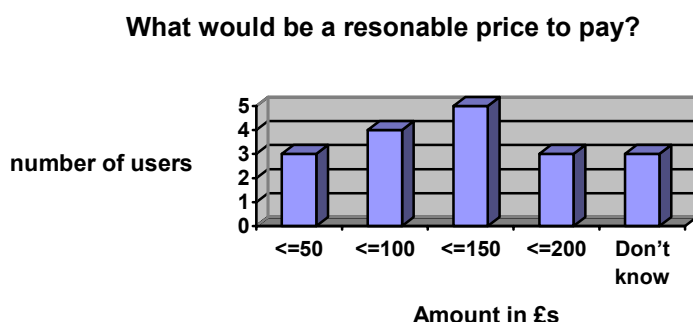
Figure 15: Showing what the users feel would be a reasonable price to pay

Participants were asked what sort of figure they might be willing to pay for a subscription to either WMSS or WDM. Four annual price bands were suggested: £50 (3/18), £60-£100 (4/18), £110-£150 (5/18) and £160-£200 (3/18). Some users felt that the sum suggested should be per module, others for the whole suite. There was a general feeling that it would all depend on what was being offered for the money and what the benefits would be. Specific comments are listed below under the category headings.

Fifty pounds
- 50 is fine, wouldn't like it to be too much higher. (2)
- £50 enough (12)
- £50 depends on what the benefits from it are going to be. If he can keep up with what he needs to know anyway then it has to make his life easier. UAP are running a web based program. You go into their intranet and they have updated labels and recommendations. Everything has to be up to date and in one place. (14)

Sixty to one hundred pounds
- £100 would be the maximum for the whole lot. It is of interest but he feels it is not for him as he has no confidence in the information it's giving him. WMSS has a long way to go to give out the correct information. Dessac is not perceived by clients to be important, it wouldn't help me gain sales with farmers. Deals mainly with small farms so this could be why. (1)
- As little as possible. He doesn't really know what he would be willing to pay. (4)
- £60-70 for each module. Depends what you get for it, how many training days and the level of the training given (11)
- £100 would be viable. Not sure what agronomists would pay. (15)
- £100 no more than that for each. So many competing sources of information. Places you could get the same from paying an agronomist so why add more to use this.

One hundred to one hundred and fifty pounds
- £100-150. If it does everything it is supposed to. CPD points add a lot of value to it. Training without that would be a disadvantage. (6)
- Training and update every year. £150. £50 is very reasonable (7)
- £150 for WDM as he is more interested in WDM (8)
- £150. (10)
- £150, for £50 he would join just to go have a look. (17)

One hundred and fifty to two hundred pounds
- £100-200. Couldn't ever charge more than that. It won't generate extra income for agronomists as they are paid by the acre. The farmers won't pay them any more. Wouldn't really be an issue at £50. (16)

- £200. Current price would be acceptable. (18)

Not sure
- Don't know. (9)
- Doesn't know. Who will subsidise the annual cost to keep it updated? He can't see us being able to sustain it with these charges. (13)

2.5 Improving DSS take up

The next set of questions tried to find out what the participants felt could be done to improve the take up of decision support systems in the UK.

2.5.1 What do you think needs to be done to improve the usage of DSS in agriculture?

There were a range of answers to this question and many participants suggested more than one approach to improving uptake. The most frequently cited ideas were to provide more of a reason and benefit for using the systems, providing more evidence that the systems work and building up trust, providing more useful functions (which again relates to perceived benefit), increased legislative pressure, simplifying the systems and integrating them with each other and with crop management systems. A variety of other issues were outlined by individual participants. All comments are detailed below.

Provide more of an incentive – more of a reason and benefit to using DSS over existing methods
- Needs a real incentive to use the software. Was keen to get involved with the trials but hasn't used it much. He has limited time. Currently uses Farmade for crop recommendations, it is easier for him just to write it out on paper, he just uses it as it is in a better format and easier to read by the client and is what the client expects. (1)
- If there is clear evidence of financial benefit. Dutch guy she knows uses one for potato blight, used it because it saved him money (6)
- It has to make your life easier. (8)
- What has to be shown is the value of them. The value to the advisor and the farmer. Is the decision they make a better one because they have it. (10)
- It has to help you in your day to day job a great deal. Give you access to a lot of information. (14)

More useful functions
- Systems that prompt you to look at things. Say Monday morning have it say to the farmer have you calculated nitrogen levels? walked fields etc, system should tell him what he has to do and when he has to do it. E.g.walk field looking for cleavers today. (2)
- You could send messages by mobile phone but he wants negative messages as well as positive. He wants to know if he doesn't have to spray as well as when he does. (2)
- Prompts and reminders should come from the software automatically, you shouldn't have to go into DESSAC, it should appear when you first switch your computer on. (2)
- You could photograph patches of weeds/disease in your crop using a digital camera and get the photo analysed to estimate cover etc of weeds and diseases in your crop, this could be done as digital cameras are getting cheaper.(3)
- If it helps with sequencing and following crops.
- Have a way of formalising the experiences of other people in similar or dissimilar situations. If he found one year something worked that could be formulised and sent to other people, it would be good to incorporate that. Tends to do that in discussions at the moment. (9)
- Try to bring local knowledge in. Make it interactive with users. Have feedback at 2 or 3 points in the season. (9)

More evidence that works/build up trust
- WMSS has to have a real benefit for him to use it. It needs more trial results to prove that by using it you get better results. He would use it if he felt that he was losing out and giving poor advice to his client if he didn't use it. (1)

- Has to be robust. Model has to be robust or people would not use it. Trial data may not help. You would need some form of validation data, you could get a farmer to use it and see what happens, but that farmer may be a terrible farmer. So you could say if you are a useless farmer this will help you (3)
- Validation data would help a lot. (4)
- Easier if you have a big company or a progressive farmer uses it first to prove it works. Her impression is other countries use DSS more than we do; the farmers are more prepared to accept them. Reliability has to be proved. (6)
- Build up confidence in the product. Someone like the tag group to trial it to make sure it worked for a year. (7)
- Proven track record would help. (8)
- Build up trust of the system. Have farmer's trial it (9)
- Have to be persuaded it will make you make better decisions. To do this roll it out and get farmers and advisors to use it. (10)
- High proportion of agronomists are still sceptical. Many think its no good, I have 30 years experience how can it be better than me. (12)

Legislation/environment
- Legislative requirement. Have an environmental link in it. It has to be demonstrated that you can benefit from using it (3)
- Legislative reasons would work. (10)
- Biggest driving factor would be public pressure and legislation. Or to qualify for environmental pay out. (14)

Make it easier to use
- Appealing to people who are into computing, feels he would need more training to get to grips with it. (1)
- The things he liked most about WMSS were the things that were easiest to use such as the encyclopaedia. That's the key issue. (4)
- Make them work and keep them simple, they have to be kept simple. If you want to get people using it. (15)
- A lot of farmers are computer phobic. They should be easy and simple to use to combat this. A bit like spoon feeding. Simplicity is key. (17)

Integrate data across systems
- Systems which need less input and run off existing info. He now uses planet for RB209, it calculates nitrogen and everything has to be added manually in this system again so he has to add all field data in this system the same as he did in WMSS and WDM (2)
- Integrating them with other arable software so you don't have to duplicate data. (5)
- One of the reasons he wouldn't use it at the moment is that he would have to duplicate the data. Make it so it can be down loaded from an existing program. If somehow you could incorporate it into the major commercial programs like Farmade or Farmplan. Could you make it an add on module. (16)

Wider applicability
- If you were able to use them across the board on all the crops you use. Too specialised at the moment. Too much bearing on wheat. Wheat is only 30-40% of his crops and it is easy to grow anyway. (5)

Provide more publicity and awareness raising/marketing
- He would rather be approached and introduced to a DSS than have to go out and look for them himself. The only other one he has heard of is N-sure? for nitrogen and WDM. Hasn't looked for n-sure as he is too lazy to go look for it even though he thought it was good when he first seen it a couple of years ago. (4)
- Something to get groups together and talking about it would be good. Go to Agronomy groups and such like to get people interacting as the audience. E.g. farmer discussion groups. (10)

- Publicity. More people who know about them the more you will have showing an interest. Most farmers are computer literate now and would like this software. They have to be made aware these programs exist. (11)
- Take it out to agronomy groups like AICC and show them what it can do, break it in gently. He has sat down and shown and explained it to a sceptical colleague and it changed his mind so you have to spend time with them. What I am doing at the moment is important or even as a 10 minute call to make sure everyone is comfortable using it. (12)
- Publicise them and train people to use them. Make sure people know they exist and are aware of their full potential (14)
- Word of mouth spreads fast. A lot of people go too him for advice at the moment and he wouldn't recommend it to anyone at the moment. He just wouldn't use it in its current state. (16)

Make it cheaper or free
- Give it away free. (14)

Keep it up to date
- Linked to the internet so that manufacturers updates happen all the time, almost real time. You have to be confident it's as up to date as it can be. (5)

Localisation
- Need to increase reliability and diversity, every farm and field are different. A lot of farmers he knows get disheartened as they think it doesn't know their farm. You need 2 levels where you get the basic recommendation then another one where you can fine tune. You have to remember there are lots of different ways of doing it. (14)

Misc
- It's a limited market. A lot of farmers are not interested as agronomists do it for them. (5)
- Your going to have to use them as it is so complicated now. (8)
- It will only get used at the beginning of the season. Don't think you'll be able to roll it out through the season. You maybe could with nitrogen and disease, with weeds you know at the start of the season so you can work a program out at the start. Time is a problem again. Scenarios at the start of season when you have time, is what you use it for. (10)
- A lot more time to be able to use them. (11)
- Doesn't think these things will ever save him time, they are only an additional think to help you. (14)
- Has to be stable (14)

2.5.2 What factors do you think contribute to the low usage of DSS in agriculture at the moment?

Respondents were also asked what they thought was contributing to the current low usage of DSS to give a different perspective on the usage question. Interestingly the answers did differ slightly from the previous question, although again there were a wide range of answers. Some of the most frequently cited reasons for the lack of use so far were: lack of publicity/awareness of DSS; lack of confidence/trust in the results; and system complexity. Other suggested causes were: lack of obvious benefits; lack of up to date information; low computer literacy in users; lack of willingness to try new things; low computer specification in industry; lack of training and support; lack of time and resources; perception that agronomists do the same job only better; and a lack of system integration.

People aren't aware that they're available
- They are not out yet. DSS are rather a growing thing. He wasn't aware there were any out there for wide usage. (3)
- People are not aware of what is out there; People have to be made aware of what is there. (4)
- Haven't been fully developed. (6)
- Not everyone knows about them. (8)
- Lack of awareness of what's available. (10)
- Most farmers have never heard of DSS. (12)

- People are not aware they exist. (15)
- Probably know there out there but not aware of what they are doing. (16)

Lack of confidence in systems
- You don't trust things unless you know they have been validated and they work. (4)
- Low reliability in the previous ones. (7)
- Confidence factor. (8)
- No confidence in the system. (9)
- Distrust of non proven systems. (10)
- It's new. A bit of mistrust of computers trying to tell them things (12)
- People are suspicious and unsure of computers and computer systems. Cost is not a big issue. Trust is.   (13)
- If we get together with the commercial boys it would be helpful as they already have the trust. (17)

Simplicity
- Aren't smooth enough, too complex. (6)
- Until recently they haven't been very good. You have to be careful not to make them too complicated. Ensure the modules, WMSS, WDM are kept separate. Don't try to be too clever. (11)
- Keep the science behind it hidden in a way so that you can go into it if you want, but keep the front screens fairly simple. They have to be easy to use. (11)
- MANNER for manure is relatively simple which makes it a good system. (11)
- Hasn't really worked a lot with DSS but feels some of them record far to much info when the basics will do. (16)
- Complexity of the programs. (17)

Need to know how it will benefit them
- The movers and shakers have to pick it up and get it moving so people know of the benefits. (3)
- People think they know there situation better than any system so why should I use it. (13)
- They have to know what they are going to get out of it rather than what it can do. What is the benefit to them? (18)
- He uses instinct a lot of the time but a computer can't do that. Bigger companies will have looked at decision support systems and thought, well were doing that already so why do we need this? Smaller farms spend time doing the job and so don't have time to look at this. (18)

They need to be seen as accurate
- These programs have to be seen as bang up to date. WDM weather data is a problem. Has to be on farm weather data and you can't predict the weather. (6)
- Weather forecasting not been good enough as weather stations on farm have been very expensive up till now.   As price comes down and they get better this will not be such an issue. Wants to be able to integrate weather station on farm straight in. (11)
- They are slow to develop and things change as the development progresses.
- They are not up to date. If she looks down the chemical list and sees all the new up to date chemicals then she would be more likely to use the system. (18)

Computer literacy
- Lots of farmers are not very good on computers. (1)
- There is lower use of computers in agriculture than other sectors. Those that use computers use them only to the level that's needed such as accounts and field records. (14)
- Although things are changing fast a lot of people are still not very computer literate. (15)
- There are still people who are not very computer literate. (16)

Unwillingness to try new things
- Farmers are naturally conservative. The average age of farmers is 56 so new things are less attractive to you at that age. He noticed that he was less open to new things after the age of 40. (3)
- If people don't like them straight away they are easily abandoned. People need to see benefits from it. He makes a decision within 15 minutes if he is going to use software or not. If WMSS

could give a selection of suggestions for BG and he could produce a program that could predict fall in BG numbers he would use it. Wants to see long term benefit of one product over another. (5)

- In agriculture there is a population of growers who are not open to new ideas. They have their own ideas and they know they work. (15)

Computer specification required to run them

- You must have a really up to date computer to run it, his last computer was 5 years old and not capable of running it, and a lot of the people he works with are still using the same as his old one. The computing power is not out there to cope in this sector. (1)
- Not technologically up to date as farmers are still using Win 98 on very old spec computers that cannot cope with these systems. (2)

Lack of training/support

- Lack of training. (2)
- Perceived lack of technical support available with such a system. (13)

Lack of time/resources
- General lack of time and resources. With some farmers agronomists make all the decisions. (2)
- Time is also an issue. They have so much paper work to do at the moment they don't want to sit at a computer, I am sure they would use it if it was simple though. (18)

Agronomists already do the same thing
- With some farmers agronomists make all the decisions. (2)
- Agronomists do everything; farmers don't really care too much. (7)
- Maybe agronomists feel they are better than the DSS. (7)

Lack of system integration
- Duplication of info, people don't want to have to enter the same data into 4 different systems. (17)

2.5.3 Would you recommend WMSS or WDM to a friend or colleague? Why?

Finally users were asked if, after their experience of using one of the two DSS they may have used in the trials, they would recommend it to a friend. This question was used to get a feeling for how useful and valuable the participants felt the systems to be. Out of the 18 participants, 12 (67%) said they would recommend the system to a friend/ colleague and 6 (33%) said they would not.

Table 2: Recommendation by occupation and previous use of DSS

	Would recommend		**Would not recommend**	
Occupation	**Used before**	**Not used**	**Used before**	**Not used**
Agronomists	5	2	2	0
Farmers	2	3	1	1
Lecturers	0	0	0	2
	7	5	3	3

Consultants and farmer respondents were equally positive. Seven of the nine agronomists (77%) and five out of the seven farmers (71%) said they would be willing to recommend the system. Previous use of a DSS also did not seem to make much difference to peoples willingness to recommend. Seven out of the ten people who had previously used a DSS before said they would recommend to others (70%) compared to five out of the eight who had not used a DSS before (62%).

The most popular reason for not recommending the systems was a lack of confidence in the results, followed by lack of robustness and usability; other reasons for not being willing to recommend the systems were their narrow focus on wheat and lack of suitability for small scale operations. The most frequently stated justifications for recommending one or both of the systems was some aspect of perceived value e.g. information, decision support; other responses suggested that recommendations would only be made when the system was finished and to people the respondent felt would be able to use it. The reasons the users gave for their answers are shown below under appropriate headings.

Negative responses

Not enough confidence in results
- Maybe WDM, not WMSS. WDM is being mentioned in his circles and it is being talked about reasonably favourably. (1)
- Not at the moment. He would show them and demonstrate it but not recommend it. It is not a dead cert that it would work like adding fertiliser to your grass will make it grow is a dead cert. He currently yield maps and has done for 6 years but wouldn't recommend it as there is no guarantee that it works. (3)
- It has problems with suggestions at the moment. (5)
- Not at the moment. Due to no confidence in results. (8)

Not robust/usable enough
- Because it has too many bugs. (5)
- Because he wouldn't use it at the moment its just not right yet especially the front page. (17)

Single crop
- WMSS is more useful if it is developed to the full extent. The problem is that it only deals with wheat. WMSS has more value as it is more planning and building up info over time.(6)

Not suitable for small farms
- It has to be kept up to date all the time as resistance is always changing. It may be more interesting on larger farms. Thinks they will be used more on larger farms as the farmer/farm manager has more input into decisions. On small farms the agronomist makes all the decisions.(1)

Misc.
- Not WDM. (6)

Positive responses

System/concept has real value
- Need strong nerves to use it as suggestions are not always what you think. He relied on WDM a lot this year. He believes that it is the way forward. (2)
- He likes the concept of it, concept is sound. (4)
- Good information in there. Clear information. (4)
- It's an interesting system and of value. They are a look see thing at the moment. (9)
- Thinks the system has real value in tackling the situation. (11)
- Makes you more aware of what you're trying to do and gives you ideas. (12)
- Her fiancé is farming so he has seen it. He was impressed with encyclopaedia. Encyclopaedia was so simplified that he recommended it to colleagues. Rotational would be of use to him more than any other part of it. (18)

When finished
- WMSS is not yet complete enough to get a lot out of it. (2)
- If it was more fully finished of then yes. (10)
- Yes. He has done already with WDM and would with WMSS as well as long as the product list is more complete. (13)
- Only if it all worked in final version. (15)

Depends on person
- To other academics she would. Smaller farmers she wouldn't recommend it to. May be good for a farmer discussion group. It could be a great teaching tool. (7)
- Thinks he would, not sure how much real use it would be to them. (12)
- Depends who it was. No to someone he would ask advice from. Yes - to someone taking on a new block of ground. (14)
- Would recommend it to the college and to the students. Students could take it home to their farmer parents and show them. (15)
- Providing they were computer literate, it's not difficult to use though if you are not familiar with computers you would get frustrated. (16)

Ease of use
It is relatively easy to use. (4)

3. Summary and discussion

This exercise is the final user based activity under the WMSS LINK project. Despite the low number of participants in the final interviews, the quantity and quality of information obtained through the interviews was high. While the sample is likely to be biased towards the more IT literature and IT interested group within the sector it is probable that it represents the type of person who will form the

vanguard of the emerging DSS user base. The data gathered in this way should provide a useful insight into the reasons for the take up of DSS in general as well as specific feedback on aspects of the WMSS interface. The data from these trials should be useful in the planning of the next phase of the WMSS development as well as providing support for the wider ArableDS dissemination approach.

3.1 Specific WMSS issues

Users were asked general questions about the usefulness of WMSS and its components and also about specific screen usability. The focus in these trials was on the suggest treatments screen and the rotational screen.

3.1.1 Suggest treatments screen

This is a problematic screen, for the WDM system as well as for WMSS. Its aim is to display a ranked list of possible treatment/cultivation plans and all the information needed to make choices between them e.g. margin, content, timing. User feedback was not entirely negative but less than half of those asked thought the screen and function was useful (39%). The comments associated with the feedback on usefulness suggest that a good deal of the problem lies in a mistrust of the output of the models rather than in the way the information is displayed e.g. "Didn't trust everything it told him to do" and with the way that chemicals were used within it "Not useful as its dealing with a very limited database". Other negative comments related to problems with running the model successfully on the users machine. On the positive side a number of users did find that the suggest treatments facility was useful in enhancing their own decision making i.e. by suggesting things that they hadn't thought of or by kick-starting the thinking process.

There was some concern that users were viewing the output of the suggest treatment screen as a concrete suggestion rather than a list of possibilities. The results suggest that while most users saw the output as a set of suggestions they could use or ignore as they chose (e.g. "It is an idea rather than you should do this"), a few saw it as more of a definite recommendation (e.g. "Thought the system tried to tell him best thing to do"). When asked if they thought a change of name would make things easier there was no clear opinion either way, there was also no clear consensus on a choice of name.

Recommendations:

- User acceptance of this facility will only increase as users gain trust in the output. Trust can be increased by making the calculations that are used more visible i.e. in the Help or Encyclopaedia. However, trust can really only be built up with time and use.

- It is very important to the development of trust in the system that users understand that the list they are shown is a set of suggestions and not recommendations. Perhaps change the title of the screen (rather than the name of the function) to 'Possible treatments' or 'Treatment ideas' and put a small rider on the screen to the effect that the list shown is not exhaustive and is based on the information available to the system.

3.1.2 Rotational Screen

Most users (15/18) liked this screen because of the ease with which they could use and interpret it (e.g. easy to understand, "Nice and clear and simple"). There was some concern among the developers however that users were misinterpreting the information on this screen and the responses to the questions suggest that this was justified. While all were aware that the screen was showing them the level of the weed problem over a rotational period most thought that it related to actual weed numbers (e.g. population of weeds to expect in that year) rather than the seed bank in the upper layers of the soil.

There were also a number of comments about the colours used to show different levels of seed bank which indicated that some found it hard to distinguish between the colours used. While some found the use of red to indicate a serious problem an intuitive system quite a high percentage (44%) were unsure

what the colours represented i.e. seed bank (e.g. Wasn't sure what the colours meant) and wanted more support to interpret the screen (e.g. Would be nice to know what they relate to in terms of numbers).

Although half of the sample were happy to optimise on margin ("margin is the main thing with growers") others would like to be able to include specific weeds in the optimisation, either to target them or to protect them.

Recommendations:
- The part of the screen showing the seed bank levels should have a label which explicitly states that the data relates to seed bank in the upper soil layers.
- Increase the difference between the colours used to represent the levels of seed bank present.
- Allow users to alter or set the colours for weed level themselves.
- Use a mouse-over to show the numbers that the colours relate to.
- Allow users to pick specific weeds to target or protect in the optimisation.

3.1.3 Which screen to open first?

There was no significant difference between the number of people who would prefer the rotational screen to be viewed first (8/18 or 44%) ("Easier to start with as it is not so complicated") and those who would prefer the in-season screen to open first (9/18 or 50%).("It's the one that you would use most often") The preference for screen does not appear to be occupation specific as an almost equal split of farmers and agronomists chose each screen.

Recommendation:
- Make choice of opening screen a user preference.

3.1.4 Usefulness of WMSS

Half of the users (9/18) felt that WMSS would be useful to them in the future. The main reasons people felt WMSS would be helpful related to the way in which it supported their understanding of weed biology (e.g. "Weed encyclopaedia best I have ever seen") and how it could be used to support the weed management planning process (e.g. "Useful tool early season"). The main reasons that people didn't think that WMSS would be helpful appear to be their lack of faith or trust in the output it provides (e.g. the main thing is that he didn't trust what it was telling him to do.) and the difficulty they find in using it (e.g. "Found it difficult to follow").

The most useful parts of WMSS appear to be the rotational screen (8/18 users) ("Gives you a more accurate and pictorial guide") and the encyclopaedia (7/18 users) ("It is so well done." "It was so easy to use."). Although there were a range of comments no single part of the system aroused a lot of negative emotion. The most frequently cited aspects of WMSS which users found least useful were the In-season screen (3/18) (" Difficult to use and not very clear"), the rotational screen (2/18) ("Didn't agree with some of the results"); system output (2/18) ("Felt that it didn't really give accurate results") and the suggest treatments function (2/18) ("Most confusing and the least helpful aspect of the system"). The comments suggested that trust or belief in the output was behind most of the negative feeling.

3.1.5 Future use of WMSS

The majority of users (72% or 13/18) said they would be likely or very likely to use WMSS in the future. The reasons people gave for believing they would use it in the future related to its value in: supporting a complex decision process ("You will have to use something like this to make sure you don't make mistakes in the future"); challenging their current way of thinking about weed management ("Challenges what your mind set is when dealing with a certain situation.") ; strategic planning of control strategies ("He would use it as a planning tool rather that something he would actually use to make decisions"); teaching ("Would use if could show it to students as an exercise"); and in dealing with unfamiliar problems ("Taking on new ground and you have a new weed spectrum you would use it for that").

The reasons people gave for not wanting to use WMSS in the future were either because they felt there were better ways of managing weeds ("Easier to just ask an agronomist or look it up in the book"), that it doesn't take data from their crop management system ("Would give it a 1 if it worked with Muddy Boots") and lack of trust in the output ("It has to give better results than it gives at the moment").

Two thirds of the respondents said they would recommend WMSS to a friend (12/18).
Consultants (7/9) and farmer respondents (5/7) were equally positive. Previous use of a DSS also did not seem to make much difference to people's willingness to recommend. The most popular reason for not recommending the systems was a lack of confidence in the results, followed by lack of robustness and usability. The most frequently stated justifications for recommending one or both of the systems was some aspect of perceived value e.g. information, decision support.

3.1.6 Who will they use it with?

Just over half of those who responded (53%) felt that they would only use the system on their own. Five respondents stated that they would use WMSS both on their own and with their clients (4 agronomists, 1 farmer), one of these said this would only be true if they needed to illustrate a particularly bad problem (agronomist). Another of the users stated that they would also like to show it to the people he sells the crops to (farmer). The lecturers stated that they would like to use it with their students as a teaching aid.

3.2 DSS in general and ArableDS

3.2.1 Previous use of DSS

Those people taking part in the interviews were split almost equally between those who had used DSS before and those who had not. Most of the agronomists had used them before (7/9) and just under half of the farmers (3/7). Neither of the lecturers had used a DSS previously. WDM had been used by over half (6/10) of those who said they had encountered a DSS in the past. The other systems encountered were Sundial, MANNER and Grainplan. Most of these systems were seen as helpful to a greater or lesser extent.

3.2.2 ArableDS

The ArableDS concept appeared to find favour with most of the respondents (17/18) and half of them said they would be interested in joining (9/18) although some were keen that the cost benefits of the exercise be demonstrated. It was interesting to note that eleven of the respondents had never heard of ArableDS, but after hearing a short description of what it was most were willing to at least consider joining. Agronomist respondents were more concerned about the costs of the system than the farmers. Four annual price bands were suggested: £50 (3/18), £60-£100 (4/18), £110-£150 (5/18) and £160-£200 (3/18). Some users felt that the sum suggested should be per module, others for the whole suite. There was a general feeling that it would all depend on what was being offered for the money and what the benefits would be. The idea of linking the training with Basis or NROSO points was raised and interestingly a couple of people explicitly mentioned the social aspect of the training.

Recommendations:
- Make sure that any available training points can be obtained by those attending training sessions.
- Include time for social interaction in the training day and make sure that this is mentioned in the publicity.

3.2.3 Improving DSS uptake

Many suggestions were made by participants on ways to improve uptake. The most frequently cited ideas were to provide more of a reason and benefit for using the systems, provide more evidence that the systems work and building up trust, providing more useful functions (which again relates to perceived

benefit), increasing legislative pressure, simplifying the systems and integrating them with each other and with crop management systems.

Some of the most frequently cited reasons for the lack of use so far were: lack of publicity/awareness of DSS; lack of confidence/trust in the results; and system complexity. Other suggested causes were: lack of obvious benefits; lack of up to date information; low computer literacy in users; lack of willingness to try new things; low computer specification in industry; lack of training and support; lack of time and resources; perception that agronomists do the same job only better; and a lack of system integration.

Recommendations:
- Increase and improve the publicity and marketing effort behind DSS releases.
- Make sure that the benefits of using DSS are fully costed and available.
- Publicise data relating to the success of the systems.
- Ensure that users can access the science behind the data appearing on DSS screens.
- Work towards integration with crop management systems.

3.3 Conclusion

The results of this final user consultation in this phase of the WMSS LINK project would appear to show that WMSS and the ArableDS initiative are generally going in the right direction. The data suggests that there are few areas of the WMSS user interface that require specific attention and that a lack of trust in the output is behind a lot of the more negative comments. Lack of trust also appears to be a major factor in the general uptake of DSS alongside a lack of understanding of the potential benefits of these systems. In summary the two most important aspects for increasing usability and use of systems appears to be giving users confidence in the results and showing them clearly what the benefits of use would be.

Section 4

The WMSS Heuristic Evaluation- June 2004

Introduction

Aim of this document

The aim of this document is to introduce the Heuristic Evaluation method carried out on the WMSS software during Spring of 2004 and to present the results of this evaluation in a useful and accessible format.

Aim of the Heuristic Evaluation

The Heuristic Evaluation carried out in Spring 2004 forms an important part of the usability testing in WMSS. It is used as an adjunct to other forms of usability testing such as user based testing, interview and workshop. It was carried out at this time during the project as the work load within the industry prevented any specifically user based activity from taking place.

The specific aim of this form of testing was to ensure that the design follows a preset set of guidelines which determines the overall usability of the user interface in WMSS.

This type of evaluation should:
a) Identify inconsistencies in the software design.
b) Identify navigational downfalls within the system.
c) Prioritise areas for upgrade.

Structure of this document

This document is divided into four sections. The first provides a brief description of the aims of the Heuristic Evaluation and the second an overview of the methods used to carry out the evaluation. Section three contains the results gained from the evaluation and Section four a summary and discussion of the results. Readers with limited time can read Section four in isolation and those who wish to examine the raw data and draw their own conclusions will find the Appendices useful.

Method

What is a Heuristic Evaluation

Heuristic Evaluation is a user interface critiquing process carried out by experts with reference to a shared set of usability guidelines or user interface design heuristics. It is generally used in conjunction with user-based methods such as interviews or workshops to ensure that all aspects of usability are covered. Heuristic Evaluation involves the systematic inspection of each screen in the target user interface using pre-defined guidelines, heuristics or rules as test criteria. Each of these guidelines, heuristics or rules are designed to identify specific problem areas within the interface design.

There are many different heuristics available in the HCI literature many of which have been produced to meet specific requirements.

Heuristics adopted for this evaluation

A number of considerations had to be taken into account before the final decision on the choice of heuristics could be made. Two of the most well- recognised sets of heuristics are those of Nielsen (1990) and Shneiderman (1996). Both sets of rules are well respected within the industry and cover all the topic areas that would be necessary for an evaluation of WMSS. However, neither of them actually provides a set of specific questions for the evaluator to address and, as a consequence of potentially different interpretations of the heuristics, both suggest the use of multiple evaluators.

A tool was required which would structure the evaluation of a single evaluator. After extensive research a tool developed by the Xerox Corporation *(http://www.stcsig.org/usability/topics/articles/he-checklist.html)* was selected for use within the project. This checklist was selected due to its structure and content. The structure of the document allows a single evaluator to work through each single question in a structured manner, thus minimising the risk of misinterpreting the heuristics. This was a key factor for the success of this evaluation as only one evaluator was available rather than the widely recommended number of four to six.

The Xerox Checklist

The original Xerox checklist contains 13 sections, each dealing with a separate facet of usability. For the purpose of the WMSS evaluation this was reduced to 9 sections. The section headings are:

- *Visibility of system status*
- *Match between system and real world*
- *User control and freedom*
- *Consistency and standards*
- *Help users recognise, diagnose and recover from errors*
- *Error prevention*
- *Recognition rather than recall*
- *Aesthetics and minimalist design*
- *Pleasurable and respectful interaction with the user*

Within each section there are a set of questions designed specifically to evaluate the usability of the interface. Not all of the questions within these sections were relevant to the WMSS system, and these were excluded from the process. A full set of questions and the reduced set used in the evaluation can be found in Appendices A and B.

Results

The results obtained from this evaluation are illustrated in Section 3 below. Each of the findings are also marked to a scale which measures the importance of the problem. The scale is 1 for very important/must be fixed, 2 for fairly important/should be fixed and 3 for not very important/fix when you have the time.

Main in season screen

Problem	Solution	Importance
Previous harvest date, sowing date and current date look too busy.	Change the design so that it follows that of weed list, field etc.	1
There is no way to re set the markers on the Yield/Margin scale	Incorporate a remove all markers button under the scale	3
There is no mouse over on the settings icon	Incorporate a mouse over	1
There are no mouse overs on the weather data or farm data icons	Incorporate mouse overs	1
The wizard icon is misleading as it is used to set and edit the weed list.	Change the icon to represent plant lists rather than the more general Wizard initially envisaged. One suggestion is an icon showing a small leafy plant with a little star in the top left hand corner (similar to Microsoft Graph Wizard) and change the mouse over to read "Edit weed list".	2
There are no mouse overs on the environmental icons	Incorporate mouse overs	1
Current date is wrong when entering the system	Current date should read as today's date	1
This page does not have a title/ header	Add a page header to tell the user they are looking at the in-season screen	2
In the tools menu there is no link to the wizard icon or the change view icon.	Add a wizard and change view option to the tools menu.	1

Initial set up screens

Problem	Solution	Importance
When first setting up WMSS there are no back buttons. The user has to click on the tree structure on the left hand side of the screen if they want to move up a level. (shell)	Incorporate back buttons in these screens in case the user chooses the wrong farm.	2
In the weed wizard step 1 screen you have to tab twice on the next button to move to the cancel button	Change tabs so that you only have to tab once to move on	3

Farm data editor screen

Problem	Solution	Importance
The ok button is located in the top right hand corner of the screen. This is not consistent with the other screens	Move the ok button to the bottom of the screen	2
This screen does not have a cancel button	Add a cancel button to the bottom of the screen beside the new ok button	1
Farm selector menu does not contain all the farms that have been set up.	Ensure all the farms created are displayed in this menu	2

Plant Observations

Problem	Solution	Importance
When tabbing through this screen the curser gets trapped in the observations grid	Incorporate a key stroke that will allow the user to get out of this grid and back to the ok button	3
There is no way of opening the drop down menus using keystrokes	Incorporate a key stroke that will allow the user to open the drop down menus and select an observation	3
The user has no way of knowing that the they can enter either Density or cover and that they should really put in a GS.	Make the dividing line between the GS section and the cover section bolder to indicate to the user that density and cover can be seen as the same type of thing. Add a heading above the two columns reading 'Enter Cover or Density'	2

League Table

Problem	Solution	Importance
When tabbing through this screen the selected button is highlighted in a different way from all of the other screens. If you switch to another program and then go back to DESSAC then it switches to the default	Highlight buttons using a dotted line just inside the outer edge of the button rather than a solid line around the outside	3
When using tabs in this screen you have to tab 23 times on the delete treatments not saved button to move on to the use selected plan button	Make the tab move after one click	3
There is no way of toggling between yield and margin using keystrokes	Allow a keystroke that will allow the user to switch between the two	3

Add Sprays

Problem	Solution	Importance
There is no remove all sprays button	Add a 'Remove all sprays' button to keep it consistent with the weed selection screen	2
You cannot access the selected chemical list using tabs	Allow the tab to enter the selected chemical list box	3
It is hard to tell what spray goes with what date as many people read upwards	Add a blank space under the last spray for the date to indicate where one ends and another begins	2
Title of this screen is edit operation. This is the same as the title of the add cultivations screen	Change the title to 'Edit spray'	2
Users have no way of knowing they cant change cultivations in the ad sprays dialogue	Grey out cultivations in the treatment list in this screen to indicate that they cannot be changed.	1
Headings within this screen are inconsistent and misleading and misplaced	'Treatment list' (on the left hand side) should be changed to 'Chemical list' and placed in the relevant window located directly above the list. Chemical list on the right hand side should be removed completely and 'Treatment plan' should be moved down to that position.	1

Add Cultivations

Problem	Solution	Importance
There is no remove all button on this screen	Add a 'Remove all' button to keep it in line with the weed selection screen	2
It is hard to tell what cultivation goes with what date as many people read upwards	Add a small blank space under the last cultivation for the date to indicate where one ends and another begins	2
Title of this screen is edit operation. This is the same as the title of the add spray screen	Change the title to 'Edit cultivation'	2
Users have no way of knowing they can't change sprays in the ad cultivations dialogue	Grey out sprays in the treatment list in this screen to indicate that they cannot be changed.	1
Headings within this screen are inconsistent and misleading and misplaced	Cultivations (on the left hand side) should be changed to Cultivations list and placed in the relevant window located directly above the list. Chemical list on the right hand side should be removed completely and Treatment plan should be moved down to that position.	1

Wizard

Problem	Solution	Importance
In create/edit weed list when you make changes to the list but not the name the message do you want to replace existing list appears. If you click No the user has no way of knowing instinctively what to do next	When the user clicks the No button on the alert box the curser should automatically jump to the weed list name box and the current name should be highlighted.	2
In the weed search box the user has to move the curser into the input box before entering search criteria.	The curser should always be located in the search box no matter what radio button has been chosen as the search type	3
You cannot see the full weed name in either list on this page as area displaying lists are not wide enough.	Expand the size of the weed list screen so that the full weed list names can be read	1
There is a step one but nothing after that	Remove the text that says Step 1 if there are not going to be any further steps	2

Settings

Problem	Solution	Importance
Numerical fields allow non-numerical input	If the user tries to input non numerical data into a numerical field an error should appear on the screen to state to the user that they must enter numerical data.	1
Users have no way of knowing what range of numbers they can enter into numerical fields	Zeros should be used to indicate to the user what can be entered. If defaults are used then zeros should only be used to indicate the range of values. E.g if the default is 7 but the system accepts decimals in that field the default should read 7.0. if the user enters a number outwith the acceptable range an error message should appear stating acceptable range	2

Spray nozzle selector

Problem	Solution	Importance
There is no cancel button on the screen	Add a cancel button to the bottom of the screen	2

Rotational

Problem	Solution	Importance
This page does not have a title/ header	Add a page header to tell the user they are looking at the rotational screen	2

Miscellaneous

Problem	Solution	Importance
Error message "product is being applied before earliest recommended growth stage" is not descriptive enough	Message could indicate what weed is causing the problem and what the earliest growth stage is	2
You can not increase or decrease the size of an active window	Allow window sizes to be increased or decreased. This will be particularly useful for people who have poor or corrected vision or eye strain problems.	3
There is no way of telling which icon on the main toolbar is currently selected	When the icon is selected the background color of the icon should change to indicate which icon is currently selected	3

Possible Bugs

- If pre harvest date and sowing date are set to close together the system seems to loose the diagrams of all the weed growth stage models held in the current list.
- The system does not save weed lists which have been created. When you shut the system down and re-open it they are no longer there.

Conclusions

The Heuristic Evaluation, based on the Xerox questionnaire, has highlighted a range of problems with the current version of the WMSS interface. Each of the problems found have been given a rating of between 1 and 3 to indicate their level of importance. The scale is 1 for very important/must be fixed, 2 for fairly important/should be fixed and 3 for not very important/fix when you have the time.

Although a number of problems have been found during the heuristic evaluation it should be noted that the total is actually low in comparison to industry averages. This would seem to indicate that the user centered design approach, adopted for the development of WMSS and the awareness of the development team of the importance of designing with users in mind, has proved to be a successful one in terms of interface design.

Of the 42 problems identified by the evaluation 31% of them were level 1, 43% were level 2 and 26% were level 3. These problems were spread quite evenly across the various screens within WMSS, with no particular areas causing great concern. A potential solution has been proposed for each problem to aid in the process of development. It should be noted however that there may be alternative solutions to some problems and that the developers should not take the suggestions as final should others prove more appropriate in practice.

In conclusion, the Heuristic Evaluation was used as an adjunct to other forms of usability testing within the WMSS project and was carried out at this time as the work load within the industry prevented any specifically user based activity from taking place. Heuristic Evaluation has been a useful tool for the analysis of the WMSS software and the low number of problems identified by it suggests that WMSS is a well designed and generally user friendly piece of software.