SESSION 4B

PREDICTION, MONITORING AND PRECISION IN CROP MANAGEMENT

Chairman:	Professor Paul Miller *Silsoe Research Institute, Bedford, UK*
Session Organiser:	Duncan Webb *Health and Safety Laboratory, Sheffield, UK*
Papers:	4B-1 to 4B-5

Early assessment of herbicide efficacy after application with ALS inhibitors – a first exploration

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ABSTRACT

Plants of *Solanum nigrum* (black nightshade) and *Polygonum persicaria* (redshank) were grown in a greenhouse until the fourth leaf stage. These plants were sprayed with a mixture of metsulfuron-methyl (100 and 75 g a.i./ha, respectively) and isodecyl alcohol ethoxylate (0.75 % *v/v*) using an air-pressured laboratory track sprayer. The level of carbon dioxide (CO_2) fixation as well as the relative quantum efficiency of photosystem II electron transport (PSII efficiency) and the relative quantum efficiency of photosystem I electron transport (PSI efficiency) were simultaneously assessed between 2 and 4 days after treatment. Measurements showed that CO_2 fixation, PSI and PSII efficiencies for treated plants were much lower than for unsprayed control plants. These results suggest that already few days after application the photosynthetic apparatus of *S. nigrum* and *P. persicaria* were affected by ALS inhibiting herbicides. An extensive set of experiments is being prepared to study these effects in more detail and to explore whether photosynthesis parameters can be used for early assessment of herbicide efficacy under field conditions.

INTRODUCTION

In 1991, herbicides accounted for almost half of the pesticide use worldwide in terms of the volume of active ingredient. Increased concerns about environmental side effects of herbicides, development of herbicide resistance in weeds and the necessity to reduce the cost of the inputs have resulted in increasing pressure on farmers to reduce the use of herbicides. The quantity of herbicides applied to crops can be reduced by cutting down the number of applications, by applying spot spraying rather than full-field applications or by using reduced dose rates. However, these methods increase the risk of inadequate control.

Therefore, weed management strategies aiming at using low herbicide doses ideally consist of a combination of two components. First, a method should be available to reliably predict the dose rate that is just appropriate for killing the weeds in the field. Second, a means should be available to verify rapidly whether or not the herbicide application will, in fact, result in the death of the weeds. Under field conditions, the visible effects of herbicide action are only apparent 10 to 20 days after spraying, which is too long a delay in the event that a second application of herbicide is necessary. An early detection method would permit a prompt second herbicide application in case of failure. This last element is of particular importance for ensuring that even though minimal doses of herbicides have been employed, there is a guarantee that the treatment will be successful in eliminating the weeds. Such a guarantee contributes to the adoption of this methodology by farmers, agricultural contractors and others.

The Minimum Lethal Herbicide Dose (MLHD) technology, developed by Plant Research International in the Netherlands (Ketel, 1996; Kempenaar *et al.*, 2002), has shown itself to be a promising decision support system leading to the use of lower rates of photosynthesis-inhibiting herbicides. This method allows the calculation of the minimum dose of a photosynthesis inhibiting herbicide needed to control a weed population. Simple and rapid measurements of photosynthetic activity are used to evaluate the efficacy of the treatment shortly after application. Only a minority of herbicides, however, act directly to inhibit photosynthesis, and photosynthesis is the only biological process in the plant whose activity can be rapidly and simply measured in the field. An obvious question is how effectively can measuring instruments and methods that work so well to measure the effect of photosynthetic herbicides work in detecting the effect of non-photosynthetic herbicides by their indirect effect on photosynthesis?

Acetolactate synthase (ALS) inhibitors are an important group of herbicides. They selectively inhibit acetolactate synthase, which is the first common enzyme involved in chloroplastidic biosynthesis of essential branched chain amino acids (valine, leucine and isoleucine). Photosynthesis is not regarded to be a primary target of ALS inhibiting herbicides, but changes in chlorophyll fluorescence responses have been observed in treated plants. Judy *et al.* (1990) found effects on the fluorescence from barley 2 h after treatment with imazaquin and Percival & Baker (1991) found effects on the fluorescence from wheat leaves 24 h after treatment with the ALS-inhibitor imazamethabenz methyl at the recommended field rates. Van den Boogaard & Harbinson (unpublished data) worked with photosystem I, which contained P700, the chlorophyll "a" dimer that functions as a primary electron donor. They observed that two days after sunflower plants (*Helianthus annus* L.) had been treated with the ALS inhibitor amidosulfuron the rate-constant for the reduction of the $P700^+$ pool decreased significantly. For rape (*Brassica napus*), though treatment with amidosulfuron had no effect on the rate-constant for $P700^+$ reduction, there was an easily detectable effect on the pattern of P700 oxidation following the start of the illumination of dark-adapted leaves (Van den Boogaard & Harbinson, unpublished data). How exactly these events are related to the primary events caused by ALS-inhibiting herbicides remains unknown. Madsen *et al.* (1995) found that photosynthetic parameters like fluorescence and carbon dioxide exchange rate were significantly affected after treatment with glyphosate, another well-known herbicide which interferes with the essential aromatic amino acid synthesis.

There are no published methods for predicting the effectiveness of an ALS treatment after a relatively short period of time. However, these previous studies have demonstrated the effects of various ALS inhibitors on photosynthesis within a few hours or days of application suggesting that photosynthetic parameters might be useful indicators of herbicidal efficacy. The purpose of this study was to determine if, how and when the photosynthetic apparatus of

Solanum nigrum (black nightshade) and *Polygonum persicaria* (redshank) were affected by ALS inhibiting herbicides.

MATERIALS AND METHODS

Plant material

S. nigrum and *P. persicaria* were raised from seeds (Herbiseed, UK) and grown in a greenhouse between January and March 2003 at Plant Research International (Wageningen, The Netherlands). The plants were grown with day/night temperatures of 18 °C / 14 °C, 70 % relative humidity and a 12 h photoperiod provided by natural light supplemented with high-pressure mercury lamps. Water and soil nutrients were kept at a level so that they were not limiting for growth.

Spraying procedure

Five week old *S. nigrum* and *P. persicaria* plants (both at the 3-leaf stage) were sprayed with an air-pressurised laboratory track sprayer delivering 400 litres/ha at 303 kPa. *S. nigrum* plants were treated with 100 g a.i./ha of metsulfuron-methyl (Ally, DuPont) and 0.75 % *v/v* isodecyl alcohol ethoxylate (Trend 90, DuPont). *P. persicaria* plants were sprayed with 75 g a.i./ha of metsulfuron-methyl and 0.75 % *v/v* isodecyl alcohol ethoxylate. Isodecyl alcohol ethoxylate is used as a surfactant to improve the uptake of metsulfuron-methyl by the leaves.

Photosynthesis measurements

To have an indication on the relative performance of the photosynthetic apparatus of ALS-treated plants the level of carbon dioxide (CO_2) fixation, the relative quantum efficiency of photosystem II electron transport (PSII efficiency) and the relative quantum efficiency of photosystem I electron transport (PSI efficiency) were assessed for both control and treated plants. Equipment similar to that described by Kingston-Smith *et al.* (1997, 1999) was used.

CO_2 fixation was measured using an infra-red gas analyser (Mark 3, Analytical Development Company, Hoddesdon UK). Actinic light was provided by a quartz halogen lamp filtered by NIR and Calfex dichroic mirrors (Balzers, Liechtenstein), and light-intensity was adjusted using metal film neutral density filters (Balzers, Liechtenstein) (Kingston-Smith *et al.*, 1997). Two wavelengths (560 and 660 nm) were used to excite the chlorophyll fluorescence in order to measure PSII efficiency. These two excitation wavelengths penetrate the leaf differently and the fluorescence they each produce is electronically recovered and displayed separately. The efficiency of PSI was measured using the irradiance-induced absorbance change around 820 nm. The CO_2 fixation and efficiency measurements were made in air consisting of 21 % (v/v) oxygen (O_2), 370 μmol/mol CO_2 with the remainder nitrogen (N_2), at a temperature of 21 to 23 °C. Photosynthesis parameters were measured when photosynthesis was in steady state after acclimatization to the irradiance level, which typically occurred after 45 to 60 mins.

The light response curves of CO_2 fixation (in $\mu mol/m^2.s$), PSI and PSII efficiency to increasing irradiance were measured for both control and treated plants of *S. nigrum* and *P. persicaria*. The actinic light source was used to provide the step increase in irradiance from 0 to 1500 µmol/m^2.s (light level step$_n$ ≈ 1.5 × light level step$_{(n-1)}$). Based on these observed light response curves a single light-intensity was selected for each species that was sufficient to saturate CO_2 fixation and which would serve as a standard irradiance for the comparison of PSI and PSII efficiencies in the presence or absence of herbicide. Once this standard had been determined the same parameters were measured at this light intensity on additional plants. For *S. nigrum* the measurements were made 2 and 3 DAT on the second or third leaf. For *P. persicaria* the measurements were made 3 and 4 DAT on the third leaf.

RESULTS

At 2 to 4 DAT CO_2 fixation, PSI and PSII efficiencies were always higher for control plants than for treated plants for both *S. nigrum* (Figure 1) and *P. persicaria* (data not shown). The rate of CO_2 fixation was most strongly reduced especially at high light intensities (light intensities from 500 to 1000 µmol/m^2.s). These results clearly demonstrate that the ALS inhibiting herbicide metsulfuron-methyl has major effects on photosynthesis. Whether these are primary or secondary effects remains unknown. Based on the light response curves for *S. nigrum* it appeared that the most appropriate light intensity for later measurements was 500 µmol/m^2.s. For *P. persicaria* the light intensity selected was 700 µmol/m^2.s.

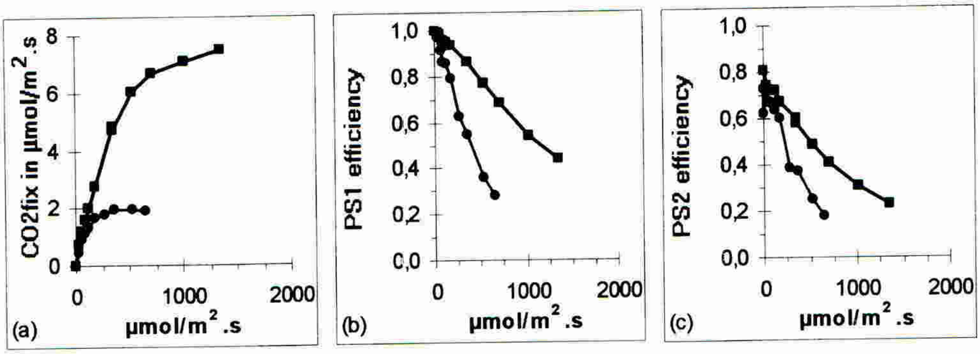

Figure 1. The effect of irradiance (µmol/m^2.s^1) on (a) CO2 fixation (µmol/m^2.s); (b) PSI efficiency; (c) PSII efficiency for one *S. nigrum* control plant (black squares) and one *S. nigrum* treated plant (3 DAT, grey circles).
Six week old plants (5 leaves, measurement on the fourth) treated with 100 g/ha metsulfuron-methyl + 0.75 % *v/v* isodecyl alcohol ethoxylate. Light intensity 500 µmol/m^2.s.

CO_2 fixation, PSI and PSII efficiencies were assessed at 2 and 3 DAT for both control (C_{SOLNI}) and treated (T_{SOLNI}) *S. nigrum* plants. For *P. persicaria* plants (C_{POLPE} and T_{POLPE}) the measurements were performed at 3 and 4 DAT. These data clearly demonstrated that for *S. nigrum* at both 2 and 3 DAT the three parameters presented here were strongly reduced by the ALS inhibiting herbicide (78 to 82 % reduction for the CO_2 fixation, 28 to 34 % reduction for the PSI efficiency and 40 to 45 % reduction for the PSII efficiency). Already 2 DAT, the differences between C_{SOLNI} and T_{SOLNI} plants were highly significant, as given in Table 1.

For *P. persicaria* the results show that 3 or 4 DAT CO_2 fixation, PSI and PSII efficiencies were reduced by the herbicide (Table 2). These reductions were only statistically significant for CO_2 fixation and PSII efficiency.

Table 1. Mean values for CO_2 fixation, PSI efficiency and PSII efficiency measured on 3 *S. nigrum* control plants (C $_{\text{SOLNI}}$) and 3 *S. nigrum* treated plants (T $_{\text{SOLNI}}$) sprayed with 100 g a.i./ha metsulfuron-methyl + 0.75 % *v/v* isodecyl alcohol ethoxylate at (a) 2 DAT and (b) 3 DAT. Light intensity 500 μmol/m^2.s.

Treatment	DAT	CO_2 fixation (μmol/m^2.s^1)	PSI efficiency	PSII efficiency
(a)				
C $_{\text{SOLNI}}$	2	5.66 ^{a}	0.759 ^{a}	0.507 ^{a}
T $_{\text{SOLNI}}$	2	1.26 ^{b}	0.543 ^{b}	0.304 ^{b}
% reduction		78 %	28 %	40 %
LSD $_{0.05}$		1.15	0.073	0.141
(b)				
C $_{\text{SOLNI}}$	3	5.76 ^{a}	0.786 ^{a}	0.512 ^{a}
T $_{\text{SOLNI}}$	3	1.05 ^{b}	0.522 ^{b}	0.282 ^{b}
% reduction		82 %	34 %	45 %
LSD $_{0.05}$		0.857	0.122	0.110

P=0.05 according to one-way ANOVA (Genstat 6)

Table 2. Mean values for CO_2 fixation, PSI efficiency and PSII efficiency measured on two *P. persicaria* control plants (C $_{\text{POLPE}}$) and three *P. persicaria* treated plants (T $_{\text{POLPE}}$) sprayed with 75 g a.i./ha metsulfuron-methyl + 0.75 % *v/v* isodecyl alcohol ethoxylate at (a) 3 DAT and (b) 4 DAT. Light intensity 700 μmol/m^2.s.

Treatment	DAT	CO_2 fixation (μmol/m^2.s^1)	PSI efficiency	PSII efficiency
(a)				
C $_{\text{POLPE}}$	3	6.33 ^{a}	0.669 ^{a}	0.443 ^{a}
T $_{\text{POLPE}}$	3	4.60 ^{b}	0.545 ^{a}	0.348 ^{b}
% reduction		27 %	18 %	21 %
LSD $_{0.05}$		1.73	NS	0.048
(b)				
C $_{\text{POLPE}}$	4	6.45 ^{a}	0.645 ^{a}	0.426 ^{a}
T $_{\text{POLPE}}$	4	4.60 ^{b}	0.536 ^{a}	0.350 ^{b}
% reduction		29 %	17 %	18 %
LSD $_{0.05}$		0.790	NS	0.045

NS : Not Significant at P=0.05 according to one-way ANOVA (Genstat 6)

DISCUSSION

This exploratory study showed that the photosynthetic apparatus of both *S. nigrum* and *P. persicaria* plants were affected by an ALS-inhibiting herbicide. The effects were detectable shortly after application (2 to 4 DAT). This indicates that there might be scope for utilising easily measured photosynthetic characteristics, such as PSII efficiency, as practical early indicators for the success of an ALS-herbicide application. Still many scientific and practical questions arose. More experiments are needed to answer questions like: "How soon after application are photosynthetic parameters affected?" or "Are photosynthetic parameters predictive enough to be used as early indicators of plants death?". An extensive set of experiments is being prepared to study these effects in more detail. Lastly, the question as to how these non-photosynthetic herbicides affect the operation of photosynthesis only a few days after application, and how different species (e.g. *Brassica* and *Helianthus*) can respond so differently, still needs to be answered.

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Automatically recording sprayer inputs to improve traceability and control

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ABSTRACT

This paper outlines the performance of a prototype device that when installed near the induction hopper of an agricultural sprayer will allow the accurate loading of the sprayer and automatic creation of spray records. The device consists of a weighing platform with an integrated RFID (Radio Frequency IDentification) read/writer. An electronic tag, attached to the chemical container, stores information about the content and recommendations for use. By placing the container on the weighing platform it is possible for the sprayer to automatically log quantities and identify the concentrate(s) loaded into the tank. Trials conducted indicate that it is possible to automatically identify and weigh the product to accuracies comparable to those of conventional methods even though the unit has to work in a vibrating and dirty environment. The information collected can be combined with location, time and weather data to form precise spray records and/or be used for improved automatic control of the sprayer, without operator intervention.

INTRODUCTION

Supply chain traceability is becoming increasingly important for all those involved with the handling of foods destined for human consumption (Hobbs *et al*., 2002). There are a number of reasons for this. From a food safety perspective, the retailer wants to ensure that products on their shelves are from known sources, are grown to specific standards particularly with regard to any residue levels, and are as fresh as possible. In the event of product problems, efficient traceability systems are vital, because the retailer/producer needs to be able to find both the source and extent of the problem, to allow efficient public notice and recall.

Traceability systems can be paper based, but these are only human readable and difficult to manage in volume. AIDC (Automatic Identification and Data Capture) technologies including Barcode and RFID (Radio Frequency IDentification) have been used extensively in the food supply chain from processor onwards to improve the management and flow of information. These trends have also been seen in agriculture. Examples include the automatic identification of animals (Rossing, 1999) for improved herd management, the Cristal Project (Debecker, 2000) implemented by ECPA to standardise the use of barcodes on pesticide containers and the Cyanamid closed transfer system incorporating RFID in kegs for improved logistics management. Animal identification is now an established component of integrated systems for livestock production and used as part of traceability systems for disease control and monitoring.

There is increasing emphasis on the use of electronic technology to automatically control and monitor tractors and implements for maximum efficiency. Precision farming systems allow variable site specific applications of inputs and the monitoring of yield (Miller, 1999). The office computer provides convenient storage for production and operation records. Integration of AIDC into these systems could allow the production of electronic records, which are ultimately destined for use in supply chain traceability systems. They may also lead to improved control of tractor and implement combinations. One particular example is that of agricultural spraying. This is a highly regulated, expensive and, should things go wrong, potentially dangerous operation. Frequently however, records are little more than paper based modifications of the agronomists recommendation.

EXPERIMENTAL METHODS

Apparatus

The basic experimental unit consists of a load cell for the determination of chemical quantity loaded, and an RFID reader for reading information from RFID tags attached to the base of chemical containers. The unit was controlled by a portable computer so as to give flexibility during the development of the system. Data is transferred from the load cell and RFID reader via a data logger to the computer which stores information to hard disk. The computer also has the capability of displaying relevant data about the quantity and types of chemical loaded in real time. A detailed description of the unit is given by Watts *et al.* (2003).

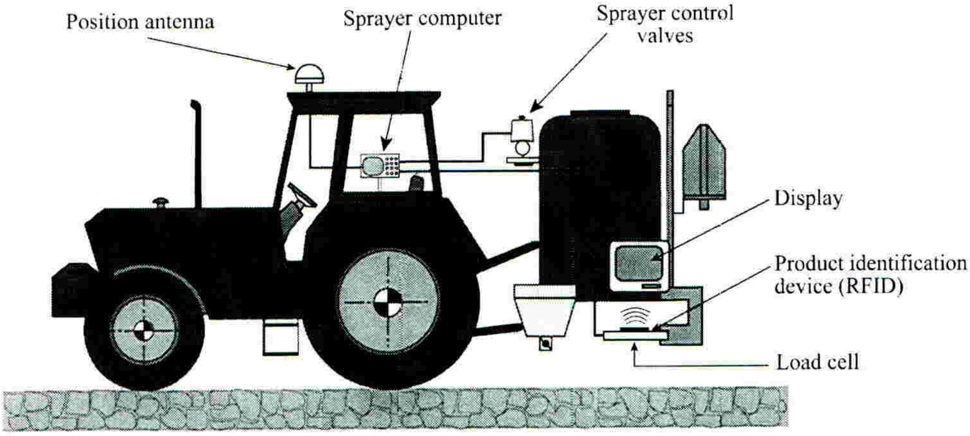

Figure 1. Diagram of experimental automatic recording apparatus.

For trials purposes, the unit was mounted near the induction hopper of a 1000 litre fully mounted sprayer. A graphical representation of the system as installed is given in Figure 1.

Procedure

The automatic recording device was compared with conventional methods of loading the sprayer using the following four criteria:

- Speed of operation;
- Reliability of recording;
- Accuracy of recording; and
- Accuracy of dispensing.

A blocked experimental design was used to enable a comparison of performance of the system with manual methods of loading, using an analysis of variance of the listed performance criteria. The experimental design took into consideration the possible effects of differences resulting from the use of water and a test liquid conforming to BS 6356-8:1996 (Anon, 1996) with a density of 0.9 kg/litre, the use of various container sizes (100 ml to 10 litres) and differing dispensing amounts of simulated chemical (50 ml to 5 litres).

For the trials, 11 sprayer operators each undertook 24 individual loading cycles of which 12 required use of the automatic recording device (procedure shown Figure 2). After completion of the loading, the operators were asked to complete a record of their actions to the minimum recommended standard as described in the Code of Practice for the Safe use of Pesticides on Farms and Holdings (Anon., 2001). This recorded the load size, chemicals used (water and test solution) and arbitrary field data.

Containers were weighed on a laboratory balance before and after each loading operation to determine the actual amount of liquid dispensed. Operators were timed for each operation, including the creation of the record. At all times during the loading operations, the tractor/sprayer combination was running, to simulate normal operating conditions.

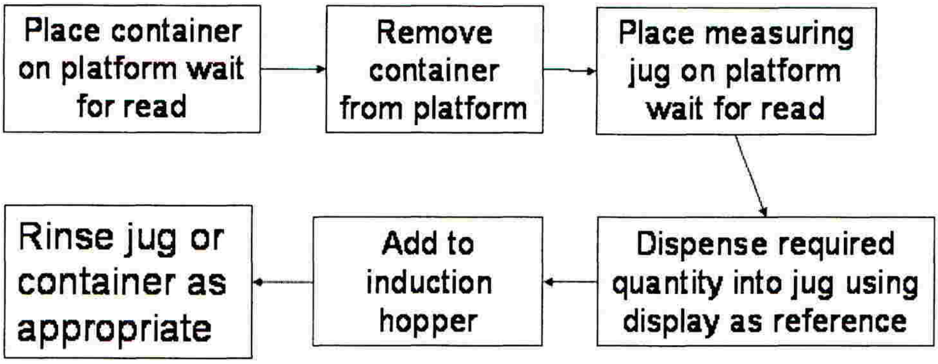

Figure 2. Procedure for the measuring of part containers with the automated recording system.

RESULTS

Accuracy of recording and speed of operation

Recorded values plotted against actual dispensed values for the automatic recording device are given in Figure 3. The data plotted has been edited to remove system errors of which 5 occurred in 264 loadings undertaken (1.8 %). These were caused either by a no read of the RFID tag (0.75 %) or when the unit entered calibration mode whilst a load with RFID tag was positioned on the platform (1.05 %).

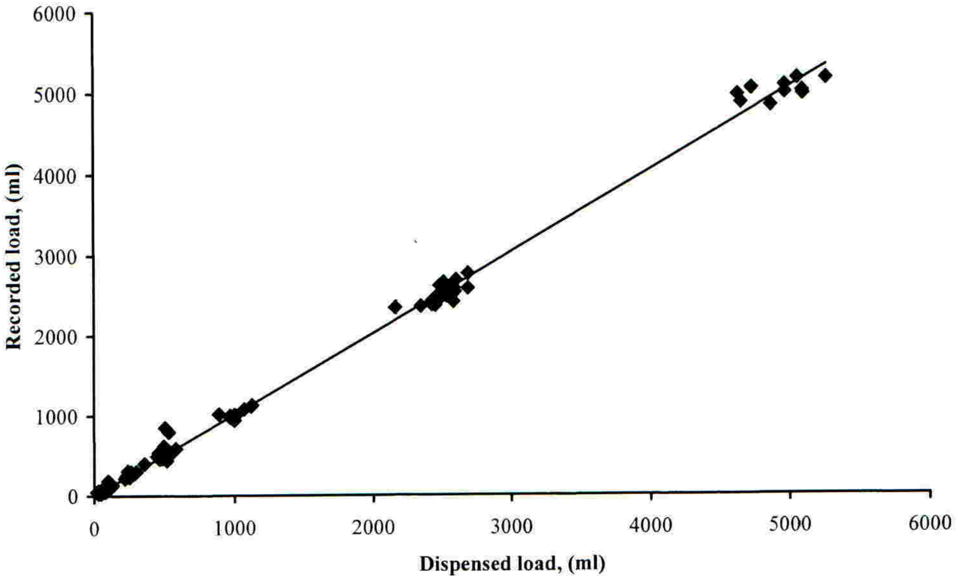

Figure 3. Dispensed and recorded loads for the automatic recording system.

An ideal loading characteristic would conform to the equation y = x, and the amount recorded would equal the amount loaded. Figures 3 and 4 give an appreciation of the levels of error found in both conventional and the automatic methods of loading and recording. The error associated with the automatic recording device was associated with factors such the accuracy of the load cell and signal processing systems used while operating in the harsh vibration environment. However, even in this environment the system performance (Figure 3) was shown to be comparable with that of conventional recording methods. The conventional recording data is given in Figure 4. It can be seen that there is only error along the x-axis (dispensed load). This was because the operator always assumed that the amount he had dispensed was the amount required, and therefore the record always represented the required amount, not the actual dispensed amount. Errors in the dispensed amount for conventional methods were mainly due to incorrect selection of measuring cylinder, or incorrect reading of measuring cylinder graduations.

Table 1 is a summary of results from the analysis of variances, showing loading time and recording accuracy information. Extra time spent at the induction hopper was a statistically significant 15 seconds per loading when using the automatic recording device. When record creation was taken into consideration, something which does not need to be done with the automatic device, average loading cycle time was reduced by 4 seconds when using the automatic device. Although not statistically significant, it indicates that the unit could have labour saving benefits.

The analysis also showed that there was no statistical difference in the accuracy of the automatic and conventional systems, or any difference between types of chemical loaded, size of container or amount dispensed.

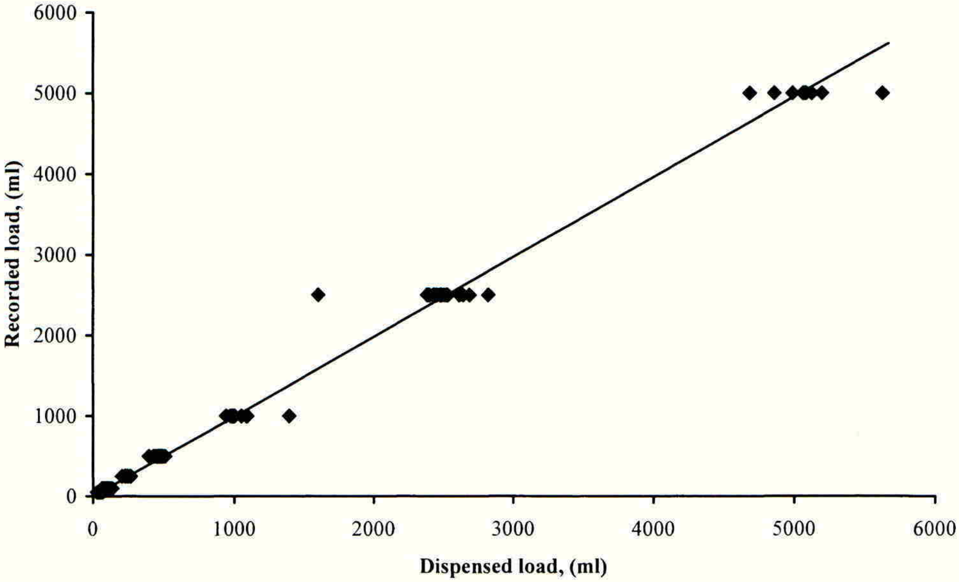

Figure 4. Plot of conventional dispensed and recorded loads.

Table 1. Summary of automatic and conventional loading data.

	Recorded Amount Mean = 1140ml	Cycle time excl. record (s)	Cycle time inc. record (s)
Automatic Mean	1134.4	68.5	68.5
Mean error (automatic)	5.6	-	-
Conventional Mean	1141	53.2	72.8
Mean Error (Conventional)	1.0	-	-
S.E.D	7.17	2.41	2.40

Failure mode analysis

The prototype device is only automatic if the operator follows a prescribed sequence when undertaking a loading. The software is not yet sufficiently comprehensive to overcome errors introduced by incorrect operation. Calibration of the load cell is programmed to occur every 70 seconds. During calibration, the platform must not have objects placed on it, leading to errors. Methods to resolve this may include allowing the operator to tare the platform manually, or modification of the program to check the presence of RFID labelled container before attempting calibration.

One RFID tag failure occurred during the trials. This only occurred after prolonged use, located on the base of the container and with no protection. It is thought that this problem will be overcome with the moulding of the RFID tag into the container during production, it is recognised that appropriate default actions will be needed for situations when the RFID tag is not read correctly or completely.

CONCLUSIONS

Trials conducted to evaluate the performance of the automatic recording device show that it is possible to use RFID technology in conjunction with load cells in the farming environment to robustly produce electronic records, which can be used in farm management software or passed through the supply chain. This was achieved without operator intervention. The accuracy of the recording was comparable with conventional methods of loading. Although time spent at the loading hopper was a statistically significant 15 seconds per cycle longer, if records are considered as part of the overall loading, the automatic unit showed a 4 second per cycle improvement on conventional methods. The data collected will also allow improved automatic setup and control of sprayer for the creation of "as applied" treatment maps based on the tanks actual active chemical contents.

It is likely that in the future, devices similar to that trialled will become commercially available with integration of the concept into the existing sprayer controller. Future work will concentrate on the production of the "as applied" application map based on actual recorded active chemical quantities, forward speed and nozzle flow rate and GPS position. Once this has been completed it will be necessary to define how information that should be passed to the supply chain.

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WMSS: Improving the precision and prediction of weed management strategies in winter dominant rotations

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ABSTRACT

Precise targeting of weed control is essential for efficient modern arable farming systems. The Weed Management Support System (WMSS) is being developed as a module of the Decision Support System for Arable Crops (DESSAC). WMSS will provide farmers and advisers with a tool to plan weed management strategies for future rotations and to optimise inputs within the current cropping year.

INTRODUCTION

Weed control is an expensive necessity within any arable farming system. Improved targeting of weed management can result in financial gain to the farmer and potential environmental benefits from increasing the biodiversity of arable land. A range of computerised Decision Support Systems (DSSs) are currently being developed. DSSs 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 (Audsley *et al.*, 1997). The Decision Support System for Arable Crops (DESSAC) aims to integrate a suite of DSS modules (Brooks, 1998). The main advantage of this integrated approach is that data common to all DSSs can be shared, and so need only be entered once.

The Weed Management Support System (WMSS) is a DSS module designed to fit within DESSAC. WMSS offers farmers, agronomists and distributors a robust tool to plan and develop weed management strategies. A rotational planning tool allows users to consider weed control options over a rotation and in more detail in the winter wheat crop by using the ‘in-season’ planning tool. Both of these parts of the system are model based, using data specific to a particular farm. The user can investigate their own scenarios by altering the model’s settings. This system will also produce a list of control strategies which aim to optimise profit margin.

Parker & Clarke (2001) showed that in the more successful DSSs users were involved in the design from conception through to delivery, ensuring the systems met the needs of their intended users. The WMSS project has followed this approach with regular user consultations and an active project management committee, including representatives from industrial and government sponsors and members of the farming industry.

Some of the key features of DSS that can commonly cause them to fail were highlighted by Parker (1999). These include poor interface design, the system being too time-consuming to use, out of date background data or science and inappropriate models. A lack of underpinning technology (e.g. computers, internet links) and a lack of integration with related software also impact the take-up of the system. WMSS has addressed these issues from early development.

User requirements

The four-year WMSS project began in October 2000 and the first user consultations took place in December 2000. The meetings were attended by a range of people who regularly make weed management decisions. These initial consultations highlighted the need for the ability to;

- investigate the effect of weed control strategies over a rotation;
- see the financial implications of actions;
- intervene and override the default values used by the models;
- enter data easily and, where appropriate, be able to import data from other systems;
- understand the assumptions made within the system;
- optimise future strategies and compare the outcomes of different options;
- manage herbicide resistance in tactical and strategic decision making.

This paper describes how these requirements are being met within WMSS.

SYSTEMS AND MODELS

When the user enters the system for the first time, they will be asked to create a list of weeds and estimate of population size for their individual fields. The management of this selection of weeds can be investigated either through a long-term rotational strategy, or by considering herbicide and cultivations control within a winter wheat crop.

System Design

WMSS consists of several modules (Figure 1), (i) biological module (BM), which contains the crop and weed models, (ii) decision module (DM), which contains algorithms that suggest a family of optimal weed control strategies and functions that evaluate profit margin, (iii) herbicide module (HM), that extracts herbicide information from the databases, and (iv) weed module (WM), that extracts weed biology information from the databases. Because WMSS operates within the DESSAC shell, information stored in the DESSAC databases is available to WMSS. The DESSAC databases accessed by WMSS comprise of a farm database, which contains data such as field information and crop observations, a local weather database, and a pesticide database, which contains regulatory information and pesticide costs. Data specific to the WMSS application are held within the WMSS databases. These include information on weed biology, herbicide efficacy, the effects of cultivation techniques on weed population dynamics, rotational information and limited spray application information.

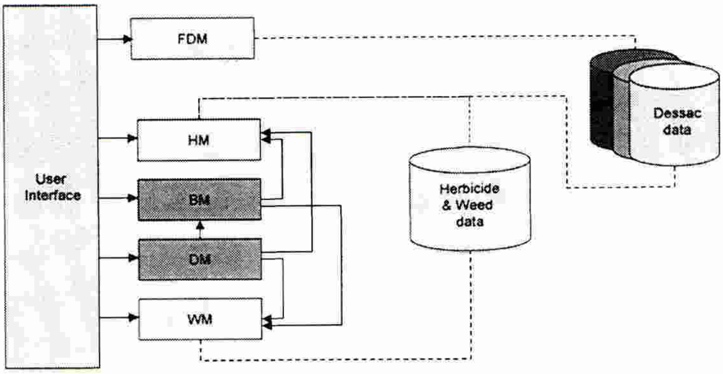

Figure 1. Schematic diagram of the WMSS system

The BM and DM access data held within the DESSAC databases and the WMSS databases through the HM and the WM. Other data used by the models, including pesticide, herbicide and weed biology data, are accessed via the HM and WM.

User Interface

The rotational screen (Figure 2) allows the user to investigate weed control strategies over a six-year rotation. Dialogue boxes enable the user to input agronomic information such as crop rotation, cultivations, drilling date and an estimate of the expected cost of weed control. The system has default values, but the information the user enters for their farm will increase the accuracy of the final output. This screen displays the simulated changes in seed bank and an estimate of profit margin for each cropping year and summarises the margin over the whole rotation, allowing the user to compare different rotational scenarios.

The 'in-season' screen (Figure 2) enables the user to investigate alternative weed control strategies in a winter wheat crop. A dialogue box allows the user to alter herbicide and cultivation programmes. Herbicide application is defined in terms of product dose and time, and cultivation in terms of type and date. Spray icons indicate when herbicides have been applied, and their effect is shown for each weed. The screen highlights the cost of each management strategy on the yield or profit margin indicator bar (Figure 2). The contribution of each weed to the yield is also shown, to check the economic necessity for controlling a particular weed.

Models

The seed bank for each weed is modelled over the rotation using a population dynamic model to estimate the risk of particular strategies, depending on the weed species present and the number of weeds observed. The user's weed observations increase the precision of the output. Calculations assessing the input to the seed bank due to seed shed and output from germination of weeds from freshly shed are included in the models. These models include components for germinability of the seeds, their longevity in the soil seed bank and density-dependent seed production. These models are also driven by the movement of the seeds within the soil following cultivations, such as inversion or non-inversion tillage. All these factors determine the number of seeds which germinate and survive to produce mature plants to contribute to the subsequent seed return and cause yield loss to the crop (Moss, 1990).

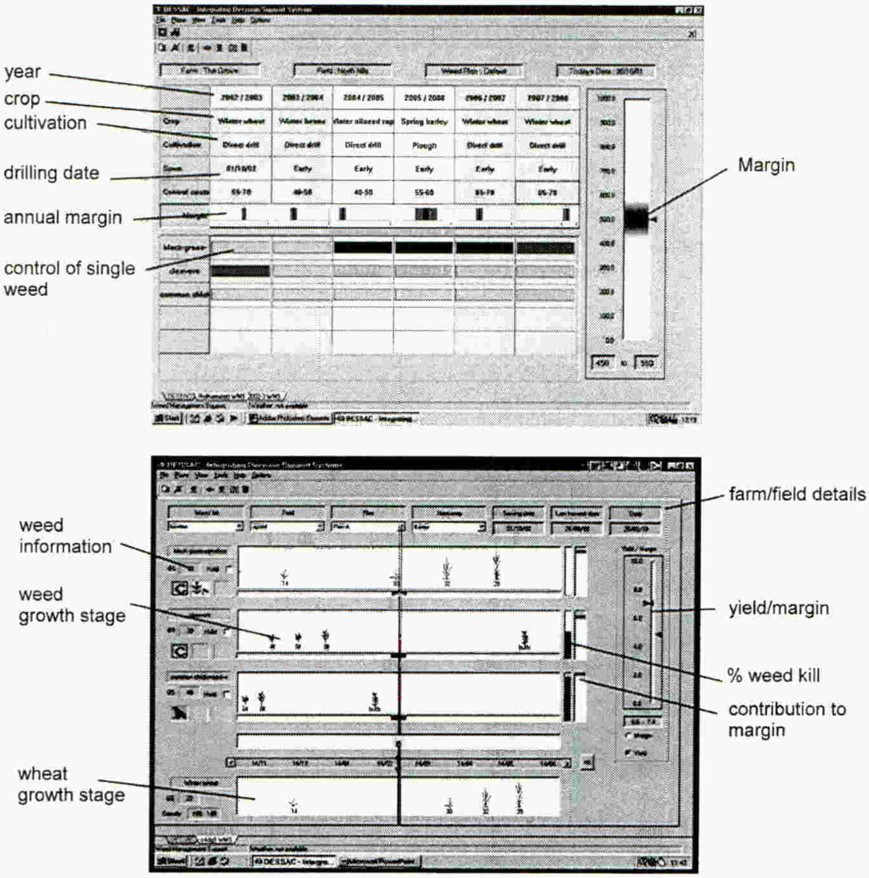

Figure 2. The provisional 'rotational' (top) and 'in-season' screens (bottom).

There are growth and competition models for both crop and weeds that are key to the 'in-season' part of the system. These require meteorological data and crop sowing date to calculate plant growth and development. The 'in-season' model is based on the INTERCOM ecophysiological model (Kropff & van Laar, 1993). WMSS initially includes parameters for 12 common arable weeds and a full range of herbicides for use in winter wheat.

Competition within a single season depends on the rate of growth of crop and weeds, which is governed by light, temperature etc. Users have access to both a long term meteorological dataset and local information. The calculated green area index and growth stages can be updated by the user, so that yield loss due to weed growth is more accurately calculated.

Resistance management plays a vital role in the decision models and was one of the key user requests. As a result, WMSS has developed a 'Resistance Risk Rating System' through consultation with research and industry to ensure that any proposed management plan will consider the risks involved. The user is notified of high-risk strategies by an alert box.

Decision Algorithms

The algorithm chosen to optimise a model-based problem will depend heavily on the model formulation and the type of decision variable (e.g. discrete, continuous or mixed). Additionally there will be computational restrictions: a user of a DSS would not expect to have to wait for a solution more than a few minutes and will only have the processing power of a standard PC.

The population dynamic model in the rotational part of the system lends itself well to a stochastic dynamic program formulation, as used by Sells (1994) for control of *Alopecurus myosurides* Huds. (black-grass) and *Avena fatua* L. (wild oats) in winter wheat. The effect of rotation is followed using seed bank numbers. In any year the seed bank may be in one of a range of values. The model calculates the probability of moving from one range to another in the next year given certain cultivations, crops or herbicide input costs. Weed control options are chosen using solution iteration strategy (Howard 1960). Profit margins from 'in-season' weed control strategies are calculated from herbicide data and biological model outputs. Standard techniques of optimisation would use too much time and memory. The WMSS 'in-season' optimisation algorithm uses expert knowledge to search and rank the solution space efficiently.

Validation of models

The information used to develop these models has been sourced from a wide range of datasets, generated mainly through Defra (UK Department for Environment, Food and Rural Affairs) funded research projects. Another user request included 'understanding and having confidence in any assumptions made within the system'. This has been addressed in WMSS by using a star rating against a particular species to indicate how much information has been available to model that species. There has obviously been more information available for the key arable species, including *A. myosuroides*, *Galium aparine* L. (cleavers) and *Stellaria media* (L.) Vill. (chickweed), but when less data are available for other species the star rating makes the user aware of this. The availability of data is a limiting factor when validating any model and we are addressing this with additional field experiments, described later in this paper. Where less information is available weeds are grouped by similar growth and habit into'functional groups'.

Validation of the system output

In order to generate additional data to validate the biological models, including herbicide effects and weed competition, field experiments were undertaken in 2002/2003 at Cambridge, Edinburgh and Hereford. The species tested include *A. myosuroides, G. aparine* and *S. media* against a range of herbicide treatments and application timings. Screening experiments have also been carried out in the glasshouses to generate data on the 'rarer' weeds of environmental importance, where information on herbicide effects was lacking.

The system output is currently being validated by experts to ensure that the decision results are logical and accurate. This will guarantee that all parts of the system are functioning correctly and the information located in the databases is accurate. The experts include weed scientists and key representatives of the farming industry with a detailed knowledge and understanding of weed management practices. Additional information providing parameters for models are sourced from published scientific literature, including previous datasets and other required information to fill gaps in the databases. All this information is subsequently validated by expert opinion.

SUMMARY

WMSS will benefit the farming industry by helping to improve the profitability of UK agriculture and assist in the Defra policy of minimum justifiable use of pesticides, while promoting arable biodiversity. The main users of WMSS will be farmers and advisers, who will directly benefit from precise and readily available information for weed management. The priorities for the remainder of the project include ensuring that the key user requirements are delivered by the time the WMSS is available commercially.

ACKNOWLEDGEMENTS

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A risk management system for controlling the foliar pests of *Brassica* crops

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ABSTRACT

Although most vegetable growers walk their crops regularly, keep records and make decisions based on their findings, there is rarely any sound statistical basis for their various approaches. In addition, the concept of 'nil tolerance', propounded by multiple retailers, does not fit easily into a sample-based system since all plants in a field would need to be sampled to be certain that none was infested. Thus, growers require a rational and statistically sound approach to crop walking and decision-making which is in line with the quality control procedures developed and used regularly by other industries. This paper describes the preliminary results of a project to develop a robust cost-effective management system for foliar pest control in *Brassica* crops. The paper focuses on the first objective of the project, which is to determine the influence of pests (principally aphids and caterpillars) on the quality of marketable crops, so that the management system can be designed to achieve an acceptable level of pest infestation in the end-product. Harvested crops (broccoli, Brussels sprout, cabbage, cauliflower) were sampled in packhouses to determine levels of pest infestation prior to despatch. Losses, due to pest damage and contamination, were measured and categorised, and compared with packhouse assessments of quality. No samples was entirely free from pests. Aphids were the most numerous pest insects and high numbers of *Brevicoryne brassicae* (cabbage aphid) and *Myzus persicae* (peach-potato aphid) were found at several sites. Caterpillars were considerably less numerous. Slugs and slug damage were also evident at several sites and, at one location, slugs had damaged 295 of 300 cabbage heads.

INTRODUCTION

In the UK, most *Brassica* crops are grown under the Assured Produce Scheme. The Assured Produce crop protocols (Anon., 2003) provide a systematic approach to help growers identify and manage the risks involved in crop production. Within the protocols, the main principle guiding pest control is that it is only necessary when the pest is present. Consequently, routine applications of insecticides at set time intervals are not advised. Regular systematic crop walking to monitor pest levels is recommended as part of the Assured Produce Integrated Crop Management (ICM) strategy. However, although most growers walk their crops regularly, keep records and make decisions based on their findings, these have no sound statistical basis. In addition, multiple retailers will not accept produce that is infested or damaged by pests ('nil tolerance'). This does not fit easily with a sample-based system, since all plants in a field would need to be sampled to be sure that none was infested. Thus, growers require a rational and statistically sound approach to crop walking and decision-making, which is in line with the quality control procedures developed and used regularly by other industries. There has been substantial development of statistical quality control techniques for industrial use (e.g. Duncan, 1974; Wetherill, 1977), which can be adapted for use in agriculture/horticulture, and some more recent development of techniques for use in crop protection (Binns *et al.*, 2000).

Management systems for foliar pests of Brussels sprout and broccoli crops have been tested with some success in experimental field plots in the UK (Blood Smyth *et al.*, 1994). However, commercial growers question their performance, particularly in situations where there is a 'nil tolerance' for pest damage. Growers are concerned about 1) the time spent inspecting crops, 2) the risks attached to 'omitting' sprays and 3) the costs of implementing such systems. They also believe that because thresholds greater than zero are used to target treatments, the system is inherently flawed. This paper describes the preliminary results of a project to develop a robust cost-effective management system for foliar pest control in *Brassica* crops. The paper focuses on the first objective of the project, which is to determine the influence of pests on the quality of marketable crops, so that the management system is designed to achieve an acceptable level of pest infestation in the end product.

MATERIALS AND METHODS

Sampling of crops from packhouses

During 2001 and 2002, samples of 32 *Brassica* crops were taken from seven packhouses to determine the percentage infestation by aphids and caterpillars prior to despatch. Each sample consisted of whole heads or an equivalent sample (sellable unit) of Brussels sprout buttons (usually 10 buttons). Samples were taken during July-December from green cabbage, cauliflower, broccoli (calabrese) and Brussels sprout crops grown in the UK (two samples of each crop type/packhouse). Samples were taken from packhouses in Kent, Lincolnshire, the Midlands and Lancashire.

To obtain a representative sample of heads of broccoli, cabbage, cauliflower or individual Brussels sprout buttons they would ideally have needed to be taken randomly from the whole batch of produce. However, this was both impractical and likely to cause problems for the packhouse staff. Therefore, sampling was based on taking whole trays of produce spread across the batch (cauliflower, cabbage and broccoli) or groups of Brussels sprout buttons spread throughout the processing of a batch. For cauliflower, green cabbage and broccoli at least 100, and more usually 300, heads were sampled on each occasion. These were obtained as full trays from each packhouse. Samples were taken from as many pallets as was practical for the packhouse. By sampling this number of units, it was possible to detect relatively low levels of pest infestation.

The samples were examined carefully in a laboratory and assessed for the presence of aphids, caterpillars and their damage. Although the project is aimed at the pest insects of *Brassica* foliage, assessments were made also of slug presence and damage. Finally, the presence of other invertebrates was also recorded.

The data were analysed to identify effects of crop (cabbage, cauliflower, broccoli and Brussels sprouts), area (Lincolnshire, Midlands, Kent and Lancashire), harvest date (July, August, September, October, November, and December), and any interactions between these effects. Unfortunately, the seasonality of some crops (broccoli, Brussels sprout) and the difficulty in collecting samples from some areas meant that it was not possible to entirely discriminate between the effects of the different factors. The numbers of samples with either aphids, caterpillars or damage were analysed as proportions of the numbers of samples assessed, within a generalised linear model (GLM) framework assuming a binomial distribution and logit link function. Separate analyses were performed for each classifying factor (crop, area, harvest date) and combination of pairs of classifying factors, for each of four variables (aphid presence, caterpillar presence, aphid damage, caterpillar damage). The mean deviances were compared with the appropriate chi-square distribution to identify statistically significant effects and differences were illustrated by calculating predicted mean proportions (expressed as percentages) for each crop, area, harvest date or combination.

RESULTS

Although the initial aim was to obtain similar numbers of samples from each area, there was a strong bias towards Lincolnshire (a major *Brassica* production area in the UK) and 17 samples (53 %) came from this area in contrast to one sample (3 %) from Kent. As a result, for the analysis, Lincolnshire was divided into two areas (Boston and Spalding). Because of the seasonality of certain crops it was not possible to differentiate between the effects of 1) crop and 2) harvest date on pest numbers.

None of the 32 samples was entirely free from pests. Aphids were the most numerous pest insects; high numbers of *Brevicoryne brassicae* (cabbage aphid; maximum 487 aphids on 300 cabbage heads) and *Myzus persicae* (peach-potato aphid; maximum 364 aphids on 3074 Brussels sprout buttons) were found at several sites. Caterpillars were considerably less numerous. *Plutella xylostella* (diamond-back moth) was the most common species (maximum 26 individuals as larvae or pupae on 300 cabbage heads). Slugs and slug damage were evident at several sites; at one location, slugs had damaged 295 of 300 cabbage heads.

The single sample from Kent produced the highest numbers of aphids (57 *B. brassicae* and 364 *M. persicae* on a sample of 3074 Brussels sprout buttons). Aphid numbers in samples from the Midlands and the Boston area were generally low. Broccoli was the crop least affected by the presence of aphids and Brussels sprout was most affected. Aphid presence (both species) was highest in July, November and December and lowest in September (Table 1). *M. persicae* was relatively more common towards the end of the year and was most numerous in Brussels sprout crops. Aphid infestation levels of 5 % or more occurred in 0/9, 4/8, 4/7 and 4/8 broccoli, Brussels sprout, cabbage and cauliflower samples respectively.

Aphid damage was higher in the Spalding area and the Midlands (Table 1). Broccoli was undamaged, whereas Brussels sprout and cabbage suffered some damage. Damage was highest in crops harvested in July/August and December and lowest in crops harvested in October. When damage levels across each complete Brusssels sprout sample (3,000 to 4,000 buttons) were estimated, they ranged from 0 to1.83 %.

Table 1. Predicted mean percentages (calculated from GLM analyses) of assessed units with aphids present, aphid damage or caterpillar damage in samples collected in different regions, from different crops and at different times of year.

Region	No. samples	Aphid presence (%)	Aphid damage (%)	Caterpillar damage (%)
Kent	1	44	0.3	11
Midlands	6	2	3	8
Boston	11	3	1	4
Spalding	6	6	3	2
Lancashire	8	6	1	1
Crop				
Broccoli	9	0.5	0	0
Brussels sprout	8	13	3	7
Cabbage	7	6	4	11
Cauliflower	8	4	0.5	0.2
Month				
July	3	6	3	4
August	7	5	2	1
September	7	1	2	6
October	10	7	0.2	6
November	4	10	2	2
December	1	22	16	1

Caterpillar numbers were low in general (< 2 % plants infested) and crops in Lincolnshire were the least infested. More caterpillars were found on cabbage than on the other crops. There was no overall temporal pattern, although the highest numbers of caterpillars were found in crops harvested in September.

Caterpillar damage was highest in Kent (one sample) and lowest in Lancashire. Cabbage and Brussels sprout crops were the most affected and damage was greatest in crops harvested in September/October. When damage levels across each complete Brusssels sprout sample (3,000 to 4,000 buttons) were estimated, they ranged from 0 to 3.8 %.

Slug damage was greatest in Brussels sprout and cabbage crops, whereas broccoli suffered no slug damage at all. All of the Brussels sprout crops suffered some damage (on average 35 % of assessed units were affected) with between 1 and 12 % of buttons affected. Overall, slugs damaged 17 % of cabbage heads. However, this mean is influenced considerably by one crop where 98 % of heads were damaged. Excluding this sample the mean was only 3 %. A mean of 1 % of cauliflower heads were damaged by slugs

A range of other species/contaminants infested the cabbage crops in particular (mean of 32 % heads infested). These included thrips, cabbage root fly and other insect species. A mean of 12 % of cauliflower crops were infested with other species followed by Brussels sprouts (6 %). Broccoli was virtually free of other species/contaminants.

To provide a comparison with the harvest data, Figure 1 gives the phenology of *B. brassicae*, *M. persicae* and all species of caterpillar on 20 insecticide-free Brussels sprout plants that were monitored weekly throughout summer 2001 at HRI Kirton (Lincolnshire). The numbers of *B. brassicae* colonies, *M. persicae* apterae and caterpillars (all species) are plotted on a log scale. It is apparent that there were two periods when aphids of both species were most numerous (approximately July and October) and aphid numbers declined considerably between these two periods. Caterpillar numbers were low, but they were most numerous in July – September.

DISCUSSION

Many of the crops taken into the packhouse were infested and damaged by pests and control was certainly much worse than the desired level indicated by multiple retailers ('nil tolerance'). Unfortunately it has not been possible to obtain many of the growers' own assessments of the produce in terms of marketability. However, a crop in which 113 aphids were found on 2 out of 300 broccoli heads was considered to be 'good', as was a cabbage crop where more than 50 heads (of 307) showed signs of slug and/or caterpillar damage.

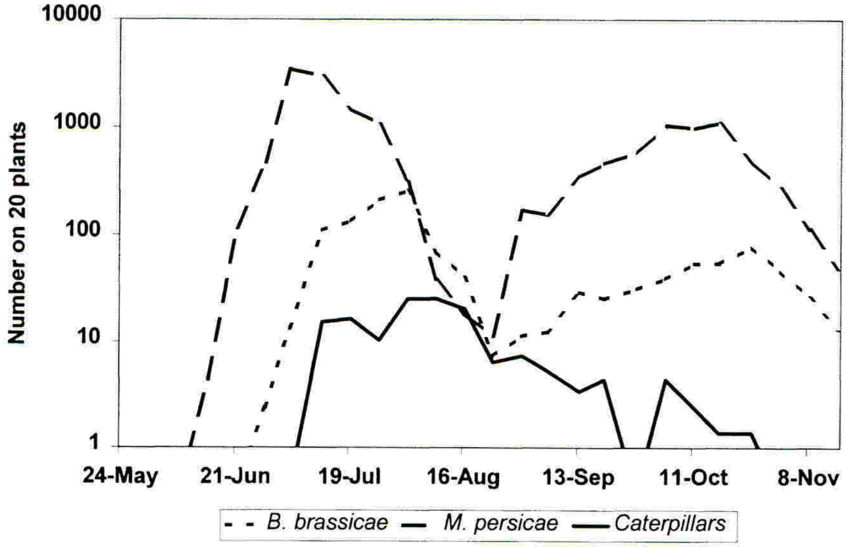

Figure 1. Phenology of pest insects on Brussels sprout plants monitored at HRI Kirton (Lincolnshire) in 2001.

Of the four crops, broccoli was affected only slightly, whereas pests and their damage were most apparent in cabbage and Brussels sprout crops. This is undoubtedly due in part to the structure of the plant, its suitability as a host for pests, the crop part that is harvested and its accessibility to insecticide sprays. The seasonality of each crop and the length of its growth cycle will also have an effect. The leafy *Brassica* crops (cabbage and Brussels sprout) were considerably more affected by slugs, whilst those with a structure providing 'funnels' (cabbage and cauliflower) were the most heavily infested with 'other pests'.

Although the timing of the peaks and troughs in aphid numbers varies from year to year and region to region, the pattern (Figure 1) is similar from year to year. The timing of infestations by *Pieris rapae* and other resident Lepidoptera also follows a predictable pattern.

P. xylostella is the least predictable species because it does not appear to overwinter successfully in the UK and is a migrant pest. The timing of the peaks and troughs is certainly reflected in the infestation levels of harvested crops and pest phenology/population dynamics is a major consideration in the development of an effective treatment strategy. Preliminary observations within this project indicate that there may be periods in the pest/crop cycle when treatments are most effective, and it is important to identify them so that interventions can be targeted for maximum impact.

During recent studies on the sampling and control of aphid and caterpillar pests in Brussels sprout crops (Collier & Mead, 1999), a threshold of 5 % plants infested was used to make treatment decisions, based on inspection of samples of 25 to 40 plants (Collier & Mead, unpublished data). The relationship between sample size and treatment threshold is fairly simple and, to maintain reproducibility, increased sample sizes are required to detect deviations from lower thresholds. Thus, a treatment threshold lower than 5 % might require growers to take very large samples (> 40 plants) that would be impossible to manage. With the exception of broccoli, aphid infestation levels of 5 % or more occurred in approximately half of the crops sampled in the present study. All of these crops were deemed suitable for harvesting and it is likely that most were sold in supermarkets. This suggests that a treatment threshold of 5 % may indeed be sufficiently low to facilitate the production of *Brassica* crops that are acceptable to multiple retailers. The next stage of this project is to determine, for each type of crop, the relationship between damage at harvest and the level of infestation allowed at various stages of crop growth, to confirm that such a threshold will be sufficiently robust for commercial use.

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Combinatorial approaches to model development for predicting emergence and crop-weed competition

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ABSTRACT

Combinatorial approaches to model development were used to predict emergence and crop-weed competition as affected by environmental factors. For emergence as affected by soil depth, the Gompertz curve was modified by incorporating either a logistic or an exponential model for parameters that varied with soil depth. This modified model simulated well the effect of soil depth on seedling emergence for rice and *Echinochloa* spp. For crop-weed competition as affected by herbicide at a range of doses, the rectangular hyperbola was modified by incorporating a logistic model for the effect of herbicide dose on winter wheat grain yield at different densities of weed infestation. This model simulated well the effect of crop-weed competition and herbicide application on grain yield.

INTRODUCTION

The prediction of biological phenomena is a key element of decision-making in agricultural practices and allows optimised use of inputs; the right amounts at the right place and time. Various approaches have been used to mathematically model biological phenomena under specific conditions. However, environmental conditions are very diverse and change dynamically with time, so more than one factor is involved, indicating that biological models must include several factors for good description and prediction. The combinatorial approach combines individual elements to produce a new structure or system which can cover varied conditions: one of its most successful applications is drug discovery using combinatorial chemistry. However, this approach has not been used widely in biological modelling. Many existing models for predicting biological effects are rather descriptive and only work well for specific conditions. Since biological phenomena are affected by a number of environmental etc. factors, such models need to be modified for accurate prediction under natural conditions. In this study, to modify the original models and incorporate the effects of other factors, combinatorial approaches were employed. First an original model was selected as a template, next the relationships between its parameters and other factors were investigated, and then mathematical models for these relationships were incorporated stepwise into the template. We have used this approach to develop models for predicting emergence and crop-weed competition with the Gompertz curve (Gompertz, 1832) and the rectangular hyperbola (Cousens, 1985), respectively, as templates.

COMBINATORIAL APPROACHES

As the template model for cumulative emergence over time, the Gompertz curve (Gompertz, 1832; equation 1) was selected: it is simple and widely used (e.g. Cussans *et al.*, 1996).

$$y = C \big/ e^{e^{-B(T-M)}} \qquad (1)$$

Here y is the cumulative emergence at days T after sowing, C is the maximum emergence, B is the rate of increase of emergence after initiation and M is a time lag to reach 50 % of the maximum cumulative emergence. Equation 1 can predict emergence over time for a specific condition. When another factor, such as soil depth (i), is involved the parameters in equation 1 will be affected. Then, equation 1 can be rewritten as equation 2, the most complex model.

$$y = C_i \big/ e^{e^{-B_i(T-M_i)}} \qquad (2)$$

If each parameter of equation 2 changes as a continuous function with the change in soil depth (i), then this change can be statistically modelled. Combinatorial model incorporation into the template model (equation 2) was conducted stepwise. First, parameter B_i was plotted against soil depth (i) to select the best model to describe the change of B with soil depth. Then, the model for parameter B was incorporated into equation 2 by replacing B_i. F-tests assessed if the new model was significantly different from its predecessor. The same method was used to incorporate parameters M_i and C_i stepwise into the template model (equation 2).

The template model for crop-weed competition was the rectangular hyperbola (equation 3), commonly used for the relationship between crop yield (Y) and initial weed density (x) (Cousens, 1985) for a crop grown at a single density. This can predict crop yield at a weed density of x, but cannot predict crop yield when another factor, such as herbicide application, is involved.

$$Y = Y_o / (1 + \beta x) \qquad (3)$$

Here Y_o is the weed-free crop yield and β is the competitivity of the weed (a weed density of $1/\beta$ reduces crop yield by 50 %). Crop yield generally increases with increasing herbicide dose as more herbicide causes a decrease in the effects of weed infestation. The herbicide may also affect the crop directly. Relationships between the parameters and herbicide dose are not known, so each herbicide dose (j) needs to be parameterised separately (equation 4).

$$Y = Y_{oj} / (1 + \beta_j x) \qquad (4)$$

Changes of parameters were investigated stepwise to select the most appropriate model for the change of each parameter with herbicide dose. Then, the selected model for each parameter was incorporated into equation 4 and F-tests were conducted to verify if the modified model was significantly different from its predecessor.

All observed data were initially subjected to analysis of variance (ANOVA). Non-linear regression was used to fit both the Gompertz curve for emergence and the rectangular hyperbola for crop-weed competition. If there was no evidence of a lack of fit for the most complex model, each model in the sequence was compared with its predecessor by calculating the F-value (equation 5). Here RSS and df are the residual sum of square and the degree of freedom, respectively, t+1 is the reduced model from its predecessor (t) and a represents ANOVA. If the F-value was lower than the tabulated F-value (5 % level) with (df_{t+1}-df_t, df_a) degrees of freedom, the reduced model was accepted.

$$F = \left(\frac{RSS_{t+1} - RSS_t}{df_{t+1} - df_t} \right) \Big/ \left(\frac{RSS_a}{df_a} \right) \qquad (5)$$

MODEL DETERMINATION

Generation of biological data

For emergence, pot experiments were conducted at the Experimental Field Station of Seoul National University in 1993. Rice (*Oryza sativa* L. cv. Dongjin) and *Echinochloa crus-galli* var *crus-galli* were sown in sandy clay loam soil at soil depths of 0.2, 1, 2, 3, 4, 6, 8, 10, and 12 cm in April/May. Pots were kept in a side-opened glasshouse with outdoor temperatures, no rain on the pots and soil water content at typical field capacity. Emerged seedlings were measured daily until 25 days after sowing. There were three replicates in a completely randomised design.

For crop-weed competition, a field experiment was conducted at Long Ashton Research Station in 1996/97. Two winter wheat cultivars (*Triticum aestivum* L. cvs. Avalon and Spark) with contrasting competitive abilities were drilled at *ca* 300 plants/m^2 in October 1996, immediately after *Brassica napus* L. (the model weed) were hand-sown. Target densities of *B. napus* were 0, 25, 50 and 100 plants/m^2. Metsulfuron-methyl (Ally®, DuPont, recommended dose 6.0 g a.i./ha) was applied at 0.375, 0.75, 1.5, 3.0 and 6.0 g a.i./ha in 250 litres/ha of water using a CO$_2$-pressurised sprayer in April 1997. Grain yield per 1 m^2 plot was measured in July 1997. There were four replicates in a split-split plot design.

Model for emergence

For each soil depth, non-linear regression analyses were used to fit the Gompertz curve (equation 1) to the emergence data for each plant species. This demonstrated that soil depth affected parameters *C* and *M* (Figure 1) but not *B* (data not shown). As *B* did not change with soil depth, it was assumed to be constant. The fit of equation 6 was not significantly worse than equation 2, so equation 2 was reduced to equation 6 with *B* constant.

$$y = C_i \Big/ e^{e^{-B(T-M_i)}} \qquad (6)$$

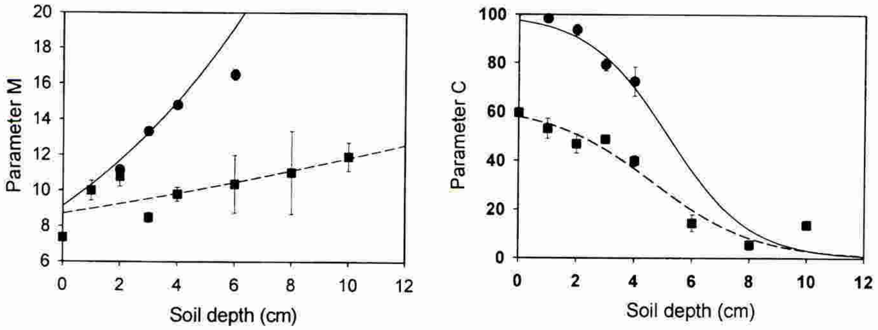

Figure 1. The relationships between soil depth and parameters *M* and *C* in the Gompertz curve. Parameters were estimated using equation 2 for rice (●) and *Echinochloa crus-galli* vars. *crus-galli* (■).

Parameter *M* increased exponentially with soil depth (Figure 1), so M_i in equation 6 was replaced by exponential curve qr^i (both q and r are unknown parameters). *F*-tests revealed that the fit of equation 7 was not significantly worse than equation 6, so the exponential increase of M was used for the delay in seedling emergence with increasing soil depth.

$$y = C_i \Big/ e^{e^{-B(T - qr^{i})}} \qquad (7)$$

Fitting equation 7 showed that C still decreased with soil depth in a logistic form. Similarly, Prostko *et al.* (1997) applied the Fermi-Dirac distribution function (a type of logistic function) to model percentage weed emergence as affected by burial depth. Thus, C_i in equation 7 was replaced by the logistic curve to give equation 8. The fit of equation 8 was not significantly worse than equation 7, so equation 2 was successfully reduced to equation 8.

$$y = \left(C_{\max} \Big/ \left(1 + \left(i/e^{n}\right)^{d}\right) \Big/ \left(e^{e^{-B(T - qr^{i})}} \right)\right) \qquad (8)$$

Model for crop-weed competition

In an initial analysis, the weed-free crop yield (Y_o) and weed competitivity (β) were estimated at each dose (j) of metsulfuron-methyl by fitting equation 4 to grain yield using non-linear regression. There was no evidence that weed-free crop yield (Y_o) was significantly affected by metsulfuron-methyl, so equation 4 was reduced to equation 9 with Y_o constant.

$$Y = Y_o \big/ \left(1 + \beta_j x\right) \qquad (9)$$

The fit of equation 9 was not significantly worse than equation 4, so there was no evidence that Y_o varied with dose (j). However, it was clear that weed competitivity (β) decreased with increasing herbicide dose in a logistic function (Figure 2). As β depends on weed biomass, we assumed that the relationship between herbicide dose and β can be modelled by the standard dose-response curve (Streibig, 1980) (equation 10).

$$\beta_j = \beta_o \Bigg/ \left(1 + \left(\frac{j}{e^{LD_{50}}} \right)^{b} \right) \qquad (10)$$

Here β_o is weed competitivity at no herbicide treatment, LD_{50} is the log of the dose required to reduce weed competitivity by 50%, and b is the response rate or steepness of the curve.

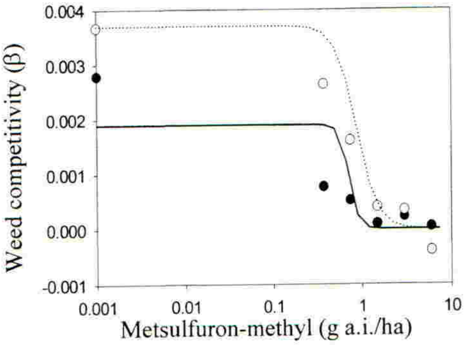

Figure 2. The relationship between weed compeitititivities (β) and metsulfuron-methyl for Avalon (●) and Spark (○).The continuous lines are fitted using equation 10. Weed competitivities are from separate analysis of grain yield by fitting equation 4 at each dose of metsulfuron-methyl.

The plot of β and herbicide dose (Figure 2) also suggested that the response of β to metsulfuron-methyl could be explained by the standard dose-response curve. Equation 10 could then be incorporated into equation 9 to give equation 11.

$$Y = Y_o \Bigg/ \left(1 + \beta_o x_o \left(1 + \left(\frac{j}{e^{LD_{50}}} \right)^b \right)^{-1} \right) \qquad (11)$$

The fit of equation 11 was not significantly worse than equation 9, so the relationship between β and herbicide dose could be explained by the standard dose-response curve (equation 10). Thus, equation 4 was successfully reduced to equation 11, which can predict crop yield as affected not only by weed density but also by herbicide dose.

MODEL APPLICATION

Using equation 8 and its parameter estimates for rice and *Echinochloa* spp, emergences of rice and *Echinochloa* spp. were simulated (Figure 3, experimental data in Kim, 1993; Kim *et al.*, 2003). The maximum percentage emergence (C_{max}) for rice was greater but decreased more rapidly with increasing soil depth than for *Echinochloa* spp. This new model successfully incorporated the effect of soil depth on emergence and can be used to predict emergences of rice and *Echinochloa* spp. seeds buried at different soil profiles.

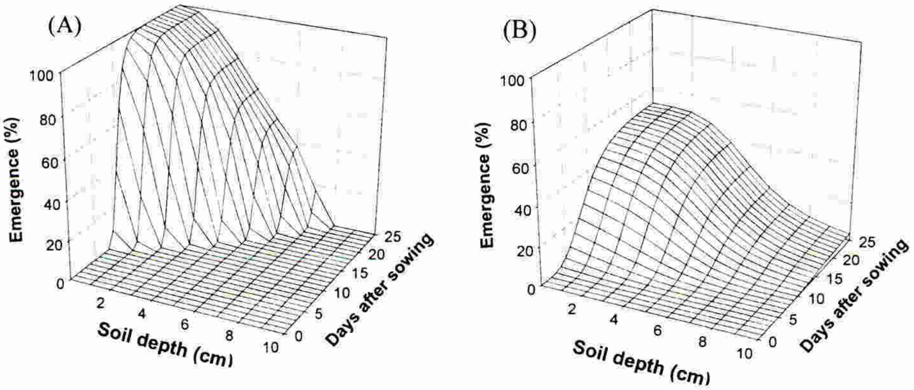

Figure 3. Simulated seedling emergences of rice (*O. sativa* cv. Dongjin) (A) and *Echinochloa crus-galli* vars. *crus-galli* (B) as affected by soil depth, using equation 8 and the parameter estimates.

For crop yield as affected by weed infestation and herbicide application, equation 11 and estimated parameters successfully simulated grain yields of two winter wheat cultivars, Avalon and Spark (Figure 4, experimental data in Kim, 1999; Kim *et al.*, 2002). There was no significant difference in weed-free grain yield of the two cultivars, while the decrease in grain yield for Spark was greater than for Avalon. At doses above 0.3 g a.i./ha the effect of weed competition was totally eradicated; equation 11 clearly simulated this aspect as well. For herbicide dose decision-making equation 11 can also be applied to determine herbicide application dose. For a given threshold of acceptable percentage yield loss (p %) equation 11 can be rearranged to give the dose (D_p) required to keep yield loss below p % (equation 12).

$$D_p = \exp(LD_{50}) \left(\frac{(100 - p)\beta_o x_o}{p} - 1 \right)^{\frac{1}{b}} \qquad (12)$$

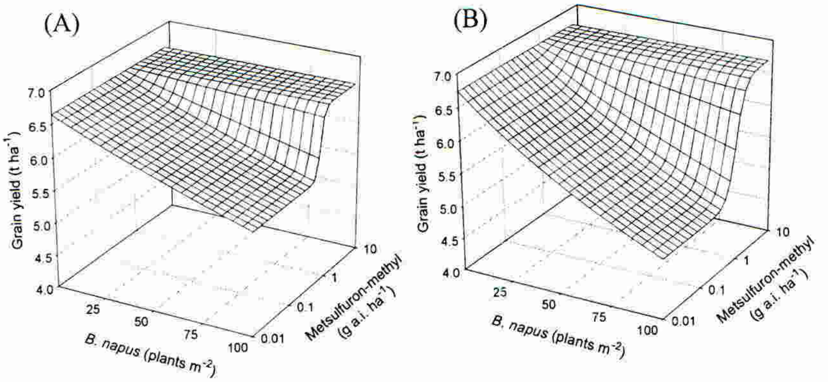

Figure 4. Predicted grain yield of Avalon (A) and Spark (B) as affected by crop-weed competition and sub-lethal doses of metsulfuron-methyl, using equation 11 and the parameter estimates.

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