SESSION 7A

PRECISION FARMING SYSTEMS

Chairman and Session Organiser	Professor P C H Miller *Silsoe Research Institute, Bedford, UK*
Papers	7A-1 to 7A-6

The patch treatment of weeds in cereals

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ABSTRACT

Larger field sizes together with the concerns about pesticide residues leaching into surface and groundwater has given impetus to research and development of measures that can reduce pesticide use in Europe. Spatially variable application or patch spraying of weeds is one of the measures that have shown potential saving of herbicide usage. Manual weed counting has been used to establish treatment maps for patch weeds. However, there is a need for development of more rational weed surveying method, e.g. using image analysis to detect species and measure density or weed coverage. Computerized decision support systems have been developed for spatial weed management and several systems have been developed as prototypes or commercial products. The ultimate goal of patch spraying is to select an efficient herbicide and an economically optimum dose for each part of the field. This goal requires, among other things, a position related decision support system that includes the yield variations in the calculations. Further the breakthrough of new technologies may lead to research and development of advanced weed control measures, such as real-time intelligent robotic weed control system.

INTRODUCTION

During the last two centuries, fields throughout Europe have been amalgamated into larger units which are now managed as one, although large within-field variation still exists. Together with the concerns about pesticide residues leaching into surface and groundwater it gives impetus to research and development of measures that can reduce pesticide use in Europe. Integrated weed management, site-specific weed management and non-chemical weed control are options that may lead to herbicide savings and diminished herbicidal loading of the environment. The development of differential global positioning systems (DGPS) and yield monitoring technologies in the late 1980's inspired several scientists, advisors and farmers to study the spatial variation of crop and soil parameters, in conjunction with weed occurrence and density.

The great within-field variance of weeds, which has been found in several studies (Nordbo *et al.*, 1995; Auld & Tisdell, 1988; Hughes, 1989; Thornton *et al.*, 1990; Wilson & Brain, 1990; Mortensen *et al.*, 1992) shows that there is good reason to believe that herbicide input can be diminished in many fields, as compared to the standard whole-field spraying. New equipment developed for patch spraying has provided a higher precision and the possibility to record and explore the responses of crop and weeds due to spatial application of herbicide (Langkilde, 1999). Herbicide savings have a direct positive impact on the costs. Whether this will show up as an increasing marginal return, depends largely on the cost of surveying the weeds but also to which extend crop yield and quality can be retained. The probable yield-reduction from a higher over-all weed pressure in a patch-sprayed field may partly be compensated by a decrease in possible direct herbicidal yield depressing effects. Also, a lower level of herbicide residues in harvested crops may be regarded as a qualitative improvement. In all cases, to manage the correct and timely spraying of small cells in the fields demands careful assessment and sound decision-making can be carried out at the tactical control level.

WEED SURVEYING METHODS

To date, several weed surveying and mapping methods may be used for patch spraying in cereals (Nordbo *et al.*, 1995; Nordmeyer *et al.*, 1996; Rew *et al.*, 1996; Christensen *et al.*, 1998). The grid weed surveying and mapping method is so far the most common method used in Europe. It involves the detection and counting of weeds prior the spraying. One advantage of this approach is the possibility to choose a herbicide, a herbicide mixture or several herbicides applicable for treating the varying weed composition and density. Further, it enables optimization of the logistics of herbicide and water volume before entering the field.

Walter (1996) suggested a concept using historical weed maps e.g. from previous years as the basis for spatial herbicide application in cereals. The author found that although the populations of dicotyledonous weed species were stationary, weed emergence varied between years, thus weed density of the species had to be measured every year. Walter *et al.* (1997) and Christensen *et al.* (1999a) used a stratified mapping method based on historical weed maps to divide the field into zones to orientate where manual weed surveying was to be carried out. Rew e*t al.* (1996) showed that visual assessment of density of couch (*Elymus repens*) could be used to map the spatial distribution of this species. Rew *et al.* (1996, 1997) described a semi-automated system of weed detection that relies on manual recognition from a vehicle. The absence of weeds, or presence of low or high weed density of blackgrass (*Alopecurus myosuroides)* couch, Italian ryegrass (*Lolium multiflorum*), bulbous oatgrass (*Arrenhenathurum elatius*), wild oat (*Avena fatua*), sterile brome (*Bromus sterilis*) and perennial thistle (*Cirsium arvense*) were recorded onto dedicated keypads mounted on the vehicle.

Manual weed counting is time consuming and thus there is a need for the development of a rational weed surveying method, e.g. using image analysis to detect and measure weed density. Thornton *et al.* (1990) was able to discriminate patches of blackgrass (*Alopecurus myosuroides*) at flowering in a winter cereal field from colour aerial photographs. Brown *et al.* (1994) used a multi-spectral still video camera from a low flying (500 to 700 m) aircraft to detect patches of weed species in corn field and maize. The species could be fairly well discriminated by their spectral characteristics of their reflectance characteristics. It must be noted that the spectral characteristics of the weeds must be sampled from the local population and statistically established shortly before the detection process, as the features are strongly variable with growth stage. With remote sensing generally only a few weed species at a certain growth stage and with a prolific growth penetrating the crop canopy can be distinguished. Patches must be comparatively large and dense. Stafford *et al.* (1997) showed the potential to discriminate between some weeds and cereal using aerial and near-ground images. The authors concluded that other methods must complement these approaches such as manual surveying.

Woebbecke *et al.* (1995) used shape feature analyses on binary images originally obtained from colour images of 10 common weeds. Shape features were generally independent of plant size, image rotation, and plant location within most images. In cereals, however, feature analyses are complicated by mutual coverage of leaves among weeds and between crop and weeds. Gerhards & Kühbauch (1993) digitised slides taken in the field and used image analysis to estimate weed and crop cover, successfully. Martin-Chefson *et al.* (1999) used image-processing techniques to discriminate between weeds and cereals, that provide the potential of mapping weed biomass of coverage.

Reflectance measurements may be used before crop-emergence or at crop ripeness. However, real time weed detection and spraying have only been developed for weed control in stubble land using simple sensors detecting green vegetation and an intermittent sprayer. Felton & McCloy (1992) have described a commercially available sprayer and its profitability has been investigated by Ahrens (1994).

Automatic detection and offset spraying for control of weeds along roadsides and public areas have been investigated by Slaughter *et al.* (1999) who developed an image-based detection system. A colour look-up table was developed from a training data set and used to categorise pixels into weed or background classes. The system was demonstrated on a commercial scale. Shape- and colour-based algorithms were used by Lee *et al.* (1999) to discriminate between weed and crop plants in tomatoes. Once weeds were located, a precision spray system applied spray liquid exclusively onto the weed plants. Video imaging was used by Giles & Slaughter (1997) to guide a precision band sprayer in row crops.

SPATIAL WEED MANAGEMENT

Computerized decision support systems offer an ideal means of achieving economical, environmentally safe, and sustainable weed management. Wiles *et al.* (1996) divided decision support systems for weed management into either efficacy-based or population-based systems. The efficacy-based systems assist decision-makers' in choosing herbicide (e.g. SELOMA, Stigliana & Resina, 1993) and herbicide dose (PC-Plant Protection, Rydahl & Thonke, 1993). Population-based models incorporate weed biology and ecology through simple deterministic models e.g. HERB (Wilkerson *et al.*, 1991) WEEDSIM (Swinton & King, 1994) GWM, PALWEED (Kwon *et al.*, 1995; Wiles *et al.*, 1996) and GESTINF (Berti & Zanin, 1997). The efficacy-based system comprises large databases with herbicide performances in different crops, weed species, growth stages etc. that enable ranking and recommendations of the most efficient herbicide or herbicide dose against a weed mixture. So far, none of these systems relate weed control to the associated yield losses. In the population-based systems, the estimated yield loss or changes in the soil seed bank without weed control define the need for weed control and determine whether a chemical or physical weed control may be beneficial.

An essential assumption in the population-based systems is a binary weed response to herbicide doses, i.e. weeds that survive a herbicide treatment (dose) have the same competitiveness and provide the same yield loss as untreated weeds (Pannell 1990; Audsley 1993; Swinton & King, 1994). However, cereal crops, which by virtue of their rapid development, high plant density and even spacing, can exert a high competitive ability, and as a consequence reduced herbicide dosages will often be sufficient to retard the growth of weeds to such an extent that they will be suppressed completely by the crop (Christensen, 1994).

A decision algorithm for patch spraying broad-leaved weeds in cereals (DAPS) has been developed at the Danish Institute of Agricultural Sciences, Research Center Flakkebjerg (Christensen *et al.*, 1996). DAPS calculates the total yield loss and finds the economical optimal dose of a herbicide or mixtures of several herbicide in all points. Weed species competitiveness, weed density, crop and herbicide price, and dose-response parameters are included in calculating the economic maximal herbicide dose. Kriging and a GIS are used to produce a treatment map for applying one herbicide or several treatment maps for applying several herbicides with an injection sprayer system.

At Silsoe Research Institute, UK, a spatial and temporal model has been developed to simulated the temporal and spatial distribution of a weed species (Paice & Day, 1997). The model describes propagation and dispersal of blackgrass and a temporal population model to estimate the yearly state variable of population cycle of blackgrass. The model is comprised of a dispersal model that manages migration between specified units, e.g. 1 m by 1 m cells. Christensen *et al.* (1999b) used the model to compare three different weed control strategies in a 140 m by 140 m area of a field with varying infestation of blackgrass. The strategies were the use of an economic threshold, the decision support system PC-Plant Protection and DAPS every year. Eight years simulation runs with site-specific weed control showed significant spatial and temporal variation in the seed bank using 1 plant/m^2 of blackgrass as the economic threshold and 3.5 l/ha of IPU beyond the threshold. The population size increased in the areas with low initial Blackgrass infestations. Further, herbicide usage increased over the eight years period with the threshold strategy. The Blackgrass population decreased using the same low IPU dose recommended by PC-Plant Protection in all cells. However, the yield loss after weed control was higher than expected indicating that the economic optimal IPU dose was higher than the recommended dose. Over an eight-year period, DAPS showed the lowest herbicide usage, lowest yield loss after spraying and lowest seed bank.

PATCH SPRAYING TECHNIQUES

In 1989, a Danish farmer develop a system for spatial application of fertilizer and pesticides. A computer program was used to divide the field into specified treatment units, e.g. 12 m by 12 m units that fitted the distance between the spray tramlines. The treatment map was edit by farmer using his knowledge about the occurrence of different weed species. The sprayer had two tanks with two pesticides or two doses of a pesticide, i.e. four treatments could be achieved including the no-spray treatment. The sprayer was mounted with two pumps and an on/off system of a dual independent nozzle system on two booms. The sprayer was controlled by a on-board computer and an treatment map.

Since 1989, several patch sprayers have been developed as prototypes or commercial products. An experimental patch spraying rig was designed and constructed at Silsoe Research Institute in 1994 to 1996. The system had been designed to use a novel injection metering system in which the liquid chemical formulation was drawn into metering cylinders mounted on the 12 m sprayer. The system was designed to operate with clean water in the spray tank. Concentrated chemical formulation was metered into the spray delivery lines by pumping water into the base of the metering cylinders to displace the active formulation, at a rate depending on speed of spraying vehicle and the dose requirements specified on a treatment map (Paice *et al.*, 1995). Further, an experimental patch sprayer in which a combination of injection metering and on/off controls both the doses rate and pesticide mixture has been constructed. The patch sprayer was controlled by a treatment map generated from field survey data and an appropriate transform to accommodate a range of factors relevant to the applied treatment. The boom was arranged in 2 m sections with each section supplied by equal lengths of small bore pipes from a central mixing chamber. The pipe size was designed to give a response time of less than 4.0 s when the sprayer was fitted with nozzles to apply 120 litres/ ha at a speed of 8 km/h.

In Denmark, collaboration between Danish Institute of Agricultural Sciences, Flakkebjerg, HARDI INTERNATIONAL, Dronningborg Industries and Datalogisk has led to development of a system in which treatment maps were generated with DAPS on the farm office computer and then downloaded to the Fieldstar unit (AGCO DK) connected to a GPS receiver in the tractor cab. The Fieldstar was connected to the Hardi Pilot that controlled the pressure of the nozzles. At each position in the field, the control system sent a message to the sprayer containing the required dose. The system has been used in three years at three locations for patch spraying dicotyledonous weed species in cereals. Currently, the system has been modified with a pulse-width modulation of the liquid flow from the nozzles developed at The University of California, Davis (Giles *et al.*, 1999). In another collaboration between Danish Institute of Agricultural Sciences, Flakkebjerg, HARDI INTERNATIONAL and Raven Industries, an injection system with five pumps and five tanks with concentrated herbicides has been used for patch spraying mixtures of weed species in cereals. Each herbicide was metered into the spray delivery lines by the individually operating pumps. A DGPS system and the software Patch Pro® (Tech International) controlled the five pumps according to a treatment map for each herbicide. Preliminary tests have shown that the pumps operate very accurately, however, there is a need for improving the cleaning methods of the system.

PATCH SPRAYING RESULTS

The potential reductions in herbicide usage that can be obtained by patch spraying depend on the density and distribution of the weed population and the strategy of spatial application of herbicides. Varying potential herbicide savings obtained in field and desk studies are shown in Table 1. In highly infested fields herbicide savings may be marginally, especially using the on/off strategy with a low economic threshold. In other fields with sparse weeds in distinct patches herbicide saving can be very high (Table 1). A more conservative strategy, that minimises the risk of weed population increase, is the species and density dependent choice of herbicide and dose.

Having selected the density-specification of a weed patch the perception scale includes a numeric and an area scale, the latter again split into one for sampling area and one for area of a treatment unit. The choice of spatial and numeric scales for a certain task is a pragmatic trade-off between the cost and benefit or saving of precision application of herbicides. Obviously, the spatial resolution of the treatment unit scale should not exceed that of the succeeding weed control technique. If, for example, the smallest area that can practically be sprayed is 2 m by 2 m, the cell should not be made less than this area. Similarly, the numeric scale of number or coverage estimation of weeds should not aim at a precision higher than that relevant for practical decision-making from an agronomic viewpoint.

Even before these resolution criteria are met, it is probable that the spatial resolution will be limited by the cost of sampling. Weeds, therefore, can only be detected with some degree of uncertainty, and it seems an inevitable part of patch spraying, in research as well as practice, to consider and evaluate the potential risk as a function of the assessment uncertainty or the chosen 'error acceptance level'.

FUTURE DIRECTIONS

Herbicide efficacy varies among weed species, which must be taken into account in spatial weed management strategies. Thus, the ultimate goal of patch spraying is to select an efficient herbicide and an economically optimum dose for each part of the field. This goal requires, among other things, a position related decision support system that includes the yield variations in the calculations.

The economic threshold concept has been used for spatial studies to decide which field areas should be sprayed or left untreated. Wiles *et al.* (1992) and Audsley (1993) used the threshold concept to simulate economic benefit of patch spraying with a single species population. Johnson *et al.* (1995) used a mean threshold value for varying mixtures of broad leaf and grass weed species to simulate the spatial variation in the need for weed control. Weed populations, however, rarely consist of single weed species or a uniform weed composition with a constant threshold. Further, the threshold concept may cause significant problems in following crops in uncontrolled areas unless there are no weeds at all. Thus, spatial weed management needs to be based on a multi-species decision model that includes the long-term effect of the level of weed control.

Experiments in winter wheat showed that the need for weed control varied among different drilling dates, seed rates and varieties (Christensen & Rasmussen, 1996). The results showed that the optimum crop competitiveness was obtained beyond a seed rate of 300 seeds/m^2 and with late sowing. However, there is a trade-off between all cropping factors and the value of crop competitiveness, which depends on the current weed population and the cost of weed control. The objectives of future research in precision weed management may be to integrate spatial crop management strategies.

Weed detection is a critical component in the utilization of the ideas developed in the research projects carried out during the last five years in Europe. Novel approaches are still needed to identify weed species and measure weed density. Cost-effective methodologies that combine automatic and manual weed surveying may also be a direction for mapping permanent and semi-permanent weed management zones, e.g. mapping areas with consistently high weed pressure, areas with consistently low weed pressure or areas with unstable weed pressure. Knowledge about the temporal and spatial stability of weed patches may be used to achieve cost-effective weed mapping (Walter, 1996).

Table 1. Herbicide saving with spatial variable application of herbicide.

Crop	Experimental layout	Decision support system	Savings	Reference
Spring barley	Complete comparison in block design	DAPS	59%	Heisel *et al.* (1997a)
Spring barley	Desk-study	DAPS	53%	Christensen *et al.* (1996)
Spring barley	Whole-field trial	DAPS	54%	Heisel *et al.* (1999)
Winter wheat	Whole-field	On/off strategy with threshold	40-50 %	Gerhards *et al.* (1995)
Winter wheat	Whole-field	On/off strategy with threshold (only C. arvense)	Potential up to 89%	Nordmeyer *et al.* (1996)
Winter wheat	Desk study	On/off strategy	9-32%	Rew *et al.* (1996)
Winter wheat	Whole field	Full rate/half rate strategy with threshold	App. 21 %	Gerhards *et al.* (1997)
Winter barley	Whole-field trial	DAPS	66 – 75%	Heisel *et al.* (1997b)
Winter barley	Desk-study	DAPS	19% vs. PCP 29% vs. Threshold	Christensen *et al.* (1999b)
1. Winter wheat 2. Maize and sugar beet	Whole-field	1. On/off strategy 2. Levels based on density	1. 54-70% 2. 25%	Gerhards *et al.* (1999)
Maize and soybean	Desk study	On/off strategy	30-72%	Johnson *et al.* (1995)
Maize	Desk-study on 12 farms	On/off strategy with threshold	71% broad-leaf 94% grass weeds	Mortensen *et al.* (1995)
Maize	Desk study	On/off strategy with threshold	40 %	Brown & Steckler (1995)
Maize	Whole field	On/off strategy with threshold	12-51 %	Williams *et al.*(1998)

The breakthrough of new technologies and demands for reduced agro-chemical input to benefit the environment and farm economy have given impetus to research and development of advanced weed control measures, e.g. the real-time intelligent robotic weed control system for selective spraying of in-row weeds using a machine vision system and a precision chemical application system (Lee *et al.*, 1999).

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Microcontroller-based multi-sensor system for online crop/weed detection

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ABSTRACT

Automatic crop-weed distinction has become increasingly important in weed control applications. A new approach based on the combination of sensors with different properties and a microcontroller hierarchy has been developed and applied.

Plants may be described in terms of their geometrical, optical and mechanical properties; each of the sensors selected is aimed at least at one of these properties. Since selectivities vary, intelligent and real-time combination of sensor signals is crucial for distinguishing weed and crops, thereby compensating for the lower selectivities of single sensors. This is achieved by an architecture utilizing high-end 8- and 16-bit microcontrollers communicating via CAN bus. The high flexibility has been enhanced by adding programmable devices, facilitating online adaption to specific crop-weed patterns. Sensors and software are being activated as required. The system is designed for speeds up to 10 km/h with a resolution of 1 sample/mm.

The multi-sensor-system has been applied to maize cultures in a greenhouse and field experiments thereby activating mechanical hoes or position sprayers. The first prototypes have been tested as mobile standalone equipment and tractor-mounted versions. The first experiments resulted in crop-weed-selectivities of above 90 %.

INTRODUCTION

Ecological as well as economical demands aim at further reduction of herbicide applications for weed control. However, the local application of herbicides as well as mechanical weed control systems strongly depend on the availability of detection systems. The corresponding sensors have to be able to distinguish between crop and weed or even recognize the different weed plants. Moreover, the detection process has to be very fast for practical applications.

Up until now no sensors have been available satisfying the above mentioned requirements with respect to quality and real time ("on-line") detection ability .

The most promising concepts for detecting single plants use optoelectronic devices, e.g. image sensors or photo diodes.

The processing of image data obtained via a video camera has been improved during recent years (Gerhards et al. 1998). However, the problems with respect to algorithms for overlapping structures and the short processing time needed for on-line detection are not yet solved. Addressable xy-imagers in CMOS technology have recently become available and have been applied to crop-weed distinction by the authors (Linz et al., 1998, see table 1). The high flexibility of these digital CMOS-cameras as well as their low price might result in a strong impact of xy-imagers for on-line image analysis.

The second concept is based on the spectral properties of plants. Due to the typical reflection in the near-infrared range caused by chlorophyll, green plants can be distinguished from soil or wheat by relative measurements (Biller et al., 1997). Such systems are commercially available for non-selective plant detection. Despite the fact that there are differences in the reflection spectra from different weeds, the application of photo diodes with mounted filters for distinguishing "green" plants from "green" weed is limited caused by the mixed spectral signature of plants and soil.

The idea of combining different sensors in order to overcome the above described disadvantages has recently been proposed by the authors (Dzinaj et al., 1998). The realisation and application of this "multi-sensor-system" is described below.

MATERIALS AND METHODS

The multi-sensor-system has been designed for high precision agricultural applications to detect single plants within row cultures for crop/weed distinction and mechanical weed control. The sensor signals are available every millimeter up to a velocity of 10 km/h.

In order to detect single plants within row cultures , the characteristics of crop and different weed plants have to be considered. The spectral, geometric or mechanical properties could vary due to their growth stages or environmental parameters. Thus a "plant database" is generated which is crucial for the application. On the other hand, each sensor - as a part of a multi-sensor-system - detects different aspects of the plants or non-target surfaces. The basic idea of the concept is the correlation of different sensor signals with respect to the plant characteristics. As an example the measured correlation of two optical sensors is shown in figure 1.

The selectivity of the sensor signals with respect to the plant characteristics vary. A single sensor signal might lead to a misinterpretation whereas the combination of all sensor signals results in a higher selectivity for crop-weed-distinction.

The system architecture is shown in figure 2. Several sensors have been tested, including various configurations with photodiodes and filters, CMOS-cameras, triangulation and ultrasonic as well as pressure sensors (Dzinaj et al., 1998). In order to avoid high volume data streams, each sensor has its own "intelligence" , namely an 8-bit microcontroller. In our application the PIC-microcontroller from Arizona Microchip Technology was used . All sensors were connected to the CAN bus via a CAN-interface. The multi-sensor-system was controlled by a powerful 16-bit host microcontroller (C167 from Siemens). Data sampling on the sensors was simultaniously triggered by a frame which is sent every millimeter by the host controller. After a signal was detected by the CAN-interface a frame with reduced signal data was returned to the host. The host combined the reduced signal data and took control over a mechanical hoe, a position sprayer or any other actuator. The distance of the actuators relative to the sensors as well as the velocity have been taken into account in the system design.

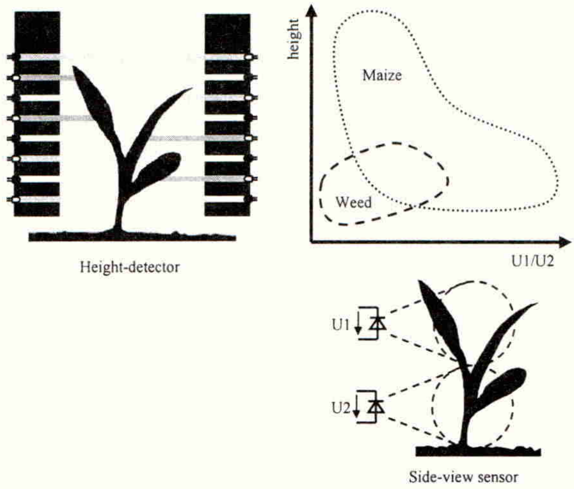

Fig.1: Measured correlation of two optical sensor signals. The information of a "Height-detector" (vertical axes) is compared to corresponding numbers obtained from "Side-view sensors" (horizontal axis).

The system is fully programmable thereby allowing a high flexibility with respect to different row cultures, growth stages or environmental influences. The application of microcontrollers has resulted in an embedded solution, no personal computer is needed for the application. The human interface is realised via a touch panel, where input and output parameters can be transfered.

The system setup consists of a learning phase, where the sensor data for a special row culture are collected without any filtering. The high-volume data are analysed ("off-line") with a PC and the corresponding correlations and thresholds are defined. These numbers are transfered to the microcontrollers and the system is applicable. Depending on properties of the field and the impact of environmental influences sensors as well as software programs can be activated or de-activated as required.

As far as possible standard sensor and electronic components have been used, thereby taking into account cost considerations as an important issue during all stages of development.

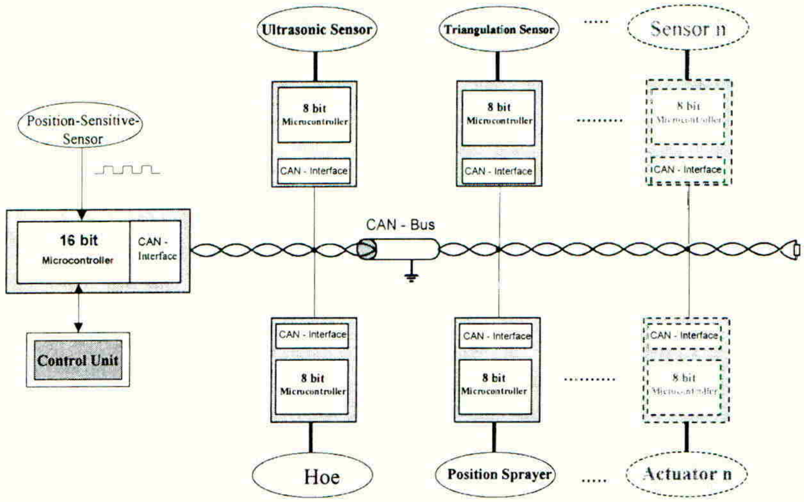

Fig.2 : Architecture of the multi-sensor-system for on-line crop/weed detection.

DISCUSSION

The method has been applied to maize cultures as test plants for row cultures. This selection has been influenced by selective geometric parameters of maize plants during the period of mechanical weed control.

Two different pieces of equipment have been constructed for use in practice (see table 1). One multi-sensor-system was mounted on a vehicle and served as a test module (Sensor Modul: "SEMO") for the implementation of new sensors or features (e.g. user interface, position sprayer, slip correction, etc.) or test runs. The position of the vehicle was determined by a position-sensitive sensor. Moreover a slip correction method has been developed by using the information from the multi-sensor-system. A second multi-sensor-system (Low Cost Modul: "LCM" ; see fig. 3) has been designed with fewer sensors and optimised with respect to lower susceptibility to malfunction. The influence of vibrations and dust or water has been investigated and taken into account. Moreover, additional functionality - including sensors - insure the reliability of the electronic signals. The LCM can be easily changed from a standalone mode for test runs (similar to SEMO) to an aggregate coupled on a wagon for agricultural tractor applications.

The multi-sensor-systems and the corresponding equipment has been tested in different stages: static and dynamic laboratory measurement setups , greenhouse and maize field. Experience with respect to sensor selectivities and disturbances have been obtained.

To our knowledge, it has been demonstrated for the first time that a single crop (in our case: maize) can be distinguished from a weed plant with an online multi-sensor system thereby controlling a mechancial actuator or a position sprayer. A prototype version of the equipment is available for determining agricultural parameters and reliability investigations.

Table 1 : Equipment for multi-sensor-systems

	SEMO (mobile sensor module)	LCM (low cost module)
Application	Data collection Test runs User Interface Slip correction	 Test runs Aggregate for tractor-mounted hoe
Applied Sensors	"Height-detector" "Side-view sensors" "Soil-plant sensor" CMOS-camera Pressure sensors Triangulation sensors Ultrasonic sensors	"Height-profile-detector" "Side-view sensors" "Soil-plant sensor" CMOS-camera
Actors	Hoe Position sprayer Acoustic or optical signals	Hoe

There is still some optimisation to be done in order to create semi-automatic adaptions of the system for different growth stages or soil structures. The corresponding task is dominated by analyzing measurement data and changing the software of the microcontroller devices. The whole system can be easily extended by connecting another sensor to the CAN-bus (see fig. 2) and modifying the corresponding host controller software. The development of a multi-sensor-system has moved strongly from hardware optimisation to software activities.

The first field experiments in a greenhouse and a test maize field have been analyzed. Preliminary results show that typically 2-5 % of the maize plants were detected as weed, while 1-8 % of weed were detected as maize. Depending on the strategy of the actuator (position sprayer, mechanical hoe) this would result in a loss of maize plants up to 5 % or an incomplete weed control of 8 %. This number strongly depends on the soil structure and the number and shape of the weed plants.

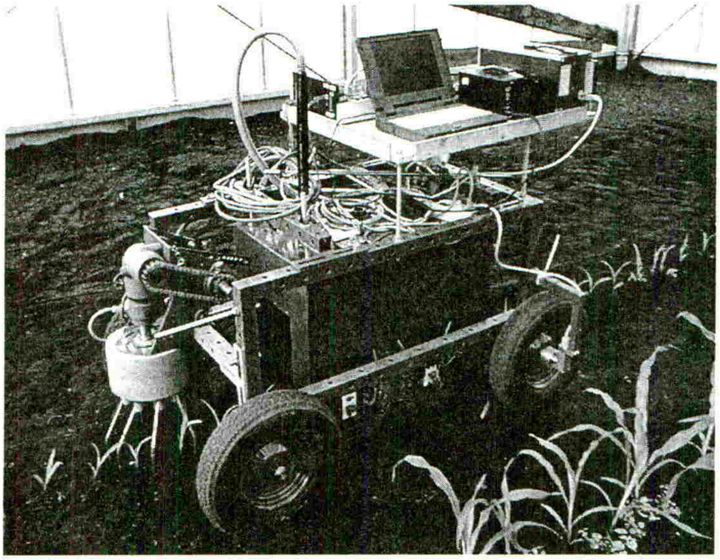

Fig.3: Low-Cost-Modul (LCM) with a mechanical actuator

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Vision system for weed detection using hyper-spectral imaging, structural field information and unsupervised training sample collection

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ABSTRACT

Restricting the spraying of herbicides to control weeds is desirable, both from an economic and environmental point of view. Using an imaging spectrograph, hyper-spectral signatures of vegetation samples are gathered online. A classifier not only distinguishes soil and vegetation but also recognises different vegetation classes.

As the reflectance of plants varies with plant stress, depending on the unknown field situation, a representative set of field samples must be collected for training on a specific field. Manually collecting a representative set of samples requires user-knowledge and time and is not economically feasible. Semi-supervised labelling based on k-means clustering, enables a system to automatically collect, label and train the classifier for a set of hyper-spectral data samples.

Using this system to selectively spray on weeds only would result in acceptable weed hit rates of 89% or higher and significant reductions in herbicide use (15-67%), depending on the actual weed density in the field.

INTRODUCTION

Growing environmental consciousness and increased competition are the driving forces behind *precision farming*. This trend encompasses efforts to decrease the use of herbicides. One of the most promising techniques toward this end is place-specific spraying, i.e. to only spray where the weed is. Studies have shown that this approach could reduce the use of herbicides for dicotyleclons (most of the vegetation) by 30-71% and for monocotyleclons (mostly grasses) by 70-94% (Johnson et al., 1995).

Initial attempts to reduce the use of herbicides were focused on distinguishing vegetation from soil. Spraying would then be restricted to patches covered with vegetation, i.e. weeds and crop. The goal of the reported work in this paper is to go a step further and also make the more subtle distinction between crop and different weeds. A few approaches have already been suggested. One approach has been based on analysing the shapes and sizes of leaves (Guyer et al., 1986; Gerhards et al., 1993; Franz et al., 1995). However, the current computational real-time requirements are probably beyond those that are economically feasible. Other research has shown that spectral reflectance of different plants may suffice to tell them apart (Knipling, 1970; Nitsch et al., 1991; Price, 1992 & 1994; Hahn & Muir, 1993). Classical multi-spectral measurement devices (like a filter wheel held before a camera) are cumbersome, slow, too expensive and too vulnerable to be mounted on a spray boom, or, as described by Felton & McCloy (1992), they suffer from having too low spatial resolution.

The work reported in this paper aimed to establish the necessary technology to achieve these goals. In particular, our aim was to design a weed sensor that was sufficiently cheap and rugged to be used on spray booms, repeated at distances of approximately 2.5 m. Real-time analysis, high crop/weed recognition rates and minimal user-interaction are required to be economically feasible.

Additional applications include selective fertilising or chemical thinning of crops (like sugar beet) or fruit (e.g. apples). In combination with a GPS positioning system, the sensor can be used to make weed maps, important tools in the decision part of the Precision Agriculture chain.

METHODS AND MATERIALS

Multi-spectral sensor

The proposed weed sensor yields the spectrum of each point on a narrow linear stripe (Battey and Slater, 1993; Herrala et al., 1994). The principle of operation is shown in Figure 1.

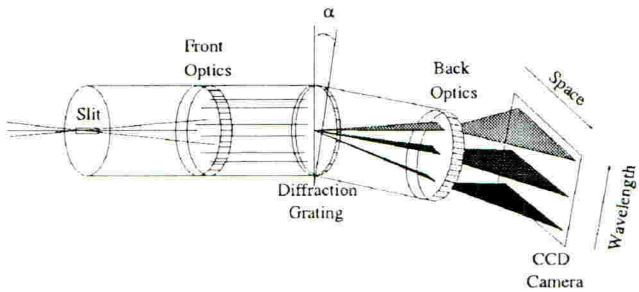

Figure 1: Working principle of imaging spectrograph

The objective lens (not shown in Figure 1) projects the image of a field patch on the slit aperture of the spectrograph. This slit extracts a small stripe from the patch on the ground.

After collimating the incoming light in the front optics, the light is split into its spectral components by a diffraction grating. The back optics form an image of the diffracted light on a monochrome camera. In this way, one of the axes of the camera acts as a spatial axis while the other camera axis is a spectral axis. The quality of front and back optics, the height above the surface and the angle of view of the objective determine the spatial resolution along the analysed stripe, while the resolution in the other direction is mainly determined by the slit width. The slit width and the number of grooves in the diffraction grating mainly determine the spectral resolution of this sensor.

It should be emphasised that the parameters of this spectrograph were designed to obtain a low cost device that should operate under normal daylight conditions with no light sources other than the sun. With a slit width of 200 μm, a slit length of 8 mm and an objective with a focal distance of 3.5 mm, it is possible to analyse a stripe having a length of 2.5 m from a height of 1 m with a spatial resolution of approximately 1.5 cm^2. The spectral range (400-1000 nm) with a resolution of about 35 nm, coincides with the typical spectral range of a camera.

The imaging spectrograph has several clear advantages over other multi-spectral sensors. It has no moving parts, resulting in high robustness with respect to vibrations of the spray boom. All the spectral information relating to the analysed surface is available at once, through diffraction of the reflected light. The limiting factor concerning speed is the frame rate of the camera. Reflectance spectra can be gathered and processed online. There is also no point in using the reflectance for all wavelengths. Computation times would be prohibitive and there is substantial redundancy in the data. The optimal set of wavelengths depends on the plants to be distinguished. One can take the wavelengths which maximise the following class-to-class separation function in which the $M_i(\lambda)$ are the mean values of the reflected light for class X and Y at wavelength λ and in which the $\sigma_i^2(\lambda)$ are the class-dependent measured variances at

$$F(\lambda) = \frac{|M_X(\lambda) - M_Y(\lambda)|}{\sqrt{\sigma_X^2(\lambda) + \sigma_Y^2(\lambda)}} \tag{1}$$

the same wavelength. Local extremes are found at certain wavelengths. The differences reflect underlying, physical differences between the plants (Hahn and Muir, 1993; Carter, 1993). Differences in the visible region are mainly determined by the plant-specific production of chlorophyll. It is even more important to analyse the reflectance in the near infrared region where the reflectance depends rather on the internal structure of the plant like the number of cell layers, the size of cells and the orientation of the cell walls. The presence of leaf hairs and waxes, characteristic for some plant species, can also influence the infrared reflectance.

Algorithms

Vegetation detection

The first step in the process is to segment the vegetation parts from the background (soil) on a pixel-by-pixel basis, using the difference in reflectance of soil and vegetation in the red and near infrared wavelength region.

Spectral reflectance of plants

Due to intensity variations of sunlight and presence of shadows yielding a higher share of shorter wavelengths in the illuminating spectrum, reflectance (relative intensity) must be measured rather than irrradiance (absolute intensity). Comparing the irradiance from each vegetation sample to the irradiance from a reference directly illuminated by the sun or illuminated with shadow, results in illumination independent spectral plant signatures. Using a data set of characteristic class spectral reflectance seems feasible. However, Carter (1993) showed that plant reflectance is affected by external factors (stress) such as nutrient and water content, competition between plants, senescence, disease levels, herbicides and soil type. Not knowing in advance the actual parameters influencing the plant reflectance makes the use of such a database impossible, as the actual field subset cannot be determined.

Scene prior knowledge

Presence of crop rows enables the use of prior knowledge about the scene, e.g. vegetation between the crop rows can only be weed. However, the position of the spray boom with respect to the crop rows is not known exactly as the spray boom moves in the horizontal and vertical planes. Therefore, the crop rows must be detected digitally by examining repetition in the distances between the geometric centres of the vegetation parts. The distance between the crop rows is repeated most if weeds are uniformly distributed over the analysed area. It needs mentioning that weeds need only be distributed uniformly on a local scale. On a field scale, they may be, and often are, localised in patches.

Practically, repetition in plant-to-plant distances is determined counting the occurrence of remainders x after division of the distance by some denominator b. The denominators can be restricted to the set of plant-to-plant distances. The error in row establishment and measurement (ε) is also included to restrict the number of evaluations even further. All distances closer than tolerance ε can be regarded as the same distance. The base with the most *almost zero* or *almost base* remainders, is probably the distance between the crop rows. In fact, the distance between row-plants can be ε larger or smaller than the average row-distance, resulting in small or very large remainders.

The proposed algorithm only holds if weed is uniformly distributed at a local scale, if the sensor is able to analyse a sufficient number of crop rows at the same time and if the weed density is sufficiently small. It is noticed that if the weed density is too high, the crop rows will not be recognised. In that case, if the number of vegetation parts is below weed tolerance, every plant sample needs to be evaluated spectrally. Otherwise, the spray nozzles can be activated immediately.

Automatic gathering and labelling of data samples

Gathering a field representative training set suffices to discriminate between all the crop and weed plants on that field. This method requires gathering of samples and training of the classifier on each field separately. Collecting samples manually is not feasible as the possible end-users do not have the time and may not always have the required knowledge.

The proposed procedure eliminates these restrictions completely. User-interaction in particular is eliminated if the crop is planted in rows. This is the case for a lot of economically important crops such as maize or sugar beet. Spot spraying with a mix of herbicides killing all the weeds in one run, is feasible if the samples can be labelled as crop or weed. The weed samples need not necessarily be grouped into the individual weed classes.

The basic principle of the algorithm is that crop only appears in the rows while weed appears both in and between the rows. Each subset (cluster) j of the collected data set consists of NT_j data samples with NR_j row-samples and $NT_j - NR_j$ between-the-row (certainly weed) samples. If V_j (Eq.2) is the relative amount of row samples in cluster j, $x_j = 1 - V_j$ is the relative amount of known weed samples in cluster j. x_j is a good first order estimate for the relative number of weed samples in the set of row samples if this subset is a good representative for the cluster population. The estimated relative number of weeds in cluster j ($\varphi_{j,weed}$) and the corresponding variance ($\sigma_{j,weed}$) are therefore calculated as in Eq.2.

$$
\begin{aligned}
V_j &= NR_j / NT_j \\
\varphi_{j,weed} &= \frac{NT_j - NR_j}{NT_j} + \frac{NR_j}{NT_j}\frac{NT_j - NR_j}{NT_j} = 1 - V_j^2 \\
\sigma_{j,weed} &= \sqrt{\frac{\varphi_{j,weed}(1-\varphi_{j,weed})}{NT_j}} = \sqrt{\frac{(1-V_j^2)V_j^2}{NT_j}}
\end{aligned}
\tag{2}
$$

Assigning a crop label to the cluster samples is acceptable if the hypothesis that the samples are weeds can be rejected on a (high) significance level (S, Eq.3) calculated as the unilateral Gaussian probability with expected number of weeds and corresponding variance.

$$
\begin{aligned}
S &= \frac{1}{\sqrt{2\pi} \cdot \sigma_{j,weed}} \int_{-\infty}^{0} e^{-\frac{(\varphi - \varphi_{j,weed})^2}{2\sigma_{j,weed}^2}} d\varphi = \frac{1}{\sqrt{2\pi} \cdot \sigma_{j,weed}} \int_{\varphi_{j,weed}}^{\infty} e^{-\frac{\varphi^2}{2\sigma_{j,weed}^2}} d\varphi \\
\varepsilon &= \frac{(NT_j - NR_j) + x_j NR_j}{NT_j} = 1 - V_j^2
\end{aligned}
\tag{3}
$$

The relative number of samples, given a crop label, labelled incorrectly (ε) is given by Eq.3. Labelling as crop after clustering the set of samples based on the spectral signatures of the samples will actually result in even more errors at low values of V_j. As crop and weeds have characteristic spectral signatures, most of the row-samples in the set of samples that are closely located to mostly weeds in the feature space, will probably be weeds also. At higher values of V_j, the error will probably be lower as there will be almost no known weed samples around in the feature neighbourhood, so that the row-samples are most likely crop.

The collected set of data samples must be split in crop and weed clusters. The k-means cluster algorithm that was used, is a stochastic algorithm in which k cluster centres are chosen randomly in a set of data samples. The cluster centres are shifted towards stable positions, minimising the summed distances between each sample and the cluster centre. Adaptation of the algorithm by choosing the initial cluster centres evenly over the subsets of row-samples and between-the-row samples, guarantees faster convergence towards crop and weed clusters. The density of the crop samples may be much lower than the density of weed samples so that random initialisation may result in only weed clusters. Each subset for which the hypothesis of weed cannot be rejected with necessary significance must be split in two subsets of which one may contain significantly more row-samples and one may contain less row-samples. As shown previously, above a certain V_j, the latter may be interpreted as a weed cluster. To keep the rejection significance high, clusters are also only split if they contain a large number of samples of which at least 10% are expected to be crop. The splitting algorithm stops if the resulting number of crop samples reaches the expected number of crop samples. This number can easily be calculated taking into account the length, width and number of analysed lines and the real row-distance and distance between crop plants in the row.

Using high weed rejection significance, most of the samples in crop labelled clusters will actually be crop samples. Also a small number of real weed samples will get the wrong labels. On the other hand, weed labelled clusters may contain some false-labelled crop samples. By iteration of the procedure, weeds will mostly be labelled as weed whereas crop will be labelled as crop or weed, resulting in small variation in labels for weed and higher variation for crop samples. The sample is finally labelled as weed if the variance is lower than the reciprocal of the number of iterations, otherwise it is labelled as crop.

RESULTS

Measurement conditions

The spectral measurements were obtained under real-field conditions: outdoor measurements for actual plants on real fields. Plant leaves and soil showed natural variation in orientation. The sun's illumination (intensity, spectrum and direction of incidence) and the vehicle speed varied while gathering the spectral data samples.

The experiments in the rest of this paper were based on reflectance measurements (reference corrected) of manually labelled plant samples on one field only. Samples were collected until a statistically relevant number of samples was obtained. The actual range of influencing factors on that field therefore most likely affects the reflectance of the samples. Special care was taken to gather a data set of only healthy looking crop and weed samples. One of the most economically important crops, sugar beet, was selected for the experiments. The data set consisted of 905 samples of *Beta vulgaris L.* (common beet), together *with Poa annua L.* (annual meadowgrass, 1830 samples), *Plantago lanceolata L.* (narrow-leaf plantain, 1412 samples), *Stellaria media L.* (common chickweed, 1019 samples*), Chenopodium album L.* (fat-hen, 867 samples) and *Polygonum persicaria L.* (Redshank, 988 samples). The plants, fully grown, varied in age from 4 to 8 weeks.

Measurements were performed using a monochrome ½" (4.8 x 6.4 mm) CCD-camera (MX5 of Adimec) coupled to the imaging spectrograph described earlier. The processing unit consisted of a 166 MHz Pentium PC with 32 Mbytes RAM.

As we were dealing with more than two classes, wavelengths were selected for each combination of crop and weed. The most separating wavelength for each pair was selected automatically. Lower ranking wavelengths were only added if they were separated by more than the spectral resolution from those already selected (higher ranked extremes). The samples were classified using a non-linear mapping neural network (Rumelhart et al., 1986) with three layers: an input layer with 5 neurons, a hidden layer with 8 neurons and an output layer with 2 neurons, one for each class (crop or weed). The training procedure was implemented with a back-propagation learning rule using an adaptive learning rate and momentum. The former minimises the learning time, the latter minimises the risk to get stuck in a local minimum of the error function.

Case study

For the experiments, data sets were created synthetically from the perfectly labelled set, containing crop and weed samples in selected amounts. Every crop sample and part of the weeds, depending on the ratio of row tolerance W (7.5 cm) and distance between the rows R (45 cm), were given a row label. The rest of the weed samples were given a between-the-row (known weed) label. This kind of labelling is possible with the algorithm presented above. The cluster procedure was repeated on data sets with different relative amounts of crop and weed samples for a fixed row width W and compared to classification, weed hit rates and herbicide reductions with perfect labelling calculated under standard conditions on sugar beet fields. The spray resolution was determined by spray width and spray length. The spray width is the size of the spray pattern along the axis of the spray boom. The resolution in the driving direction (spray length) was determined by the size of the spray pattern in that direction, the on/off frequency of the spray nozzle in combination with the driving speed and the set-up time for a stable spray pattern. A planar spray pattern, extremely small in the driving direction and stable within milliseconds, has an achievable on/off frequency, limited by fluid dynamics, of 15 Hz. Driving at a speed of 4.05 km/h resulted in a spray length of 7.5 cm.

Table 1: Classification results, hit rate and herbicide reduction for varying weed density after proposed labelling (left) and perfect labelling (right)

Weed density (# m^{-2})	**12**	**37**	**86**	**Weed density (#/m^{-2})**	**37**
Proposed labelling				*Perfectly labelled*	
Sugar beet	97	97	99		
Weed	95	96	97		
Weed in row as weed	70	75	85		
Average No of clusters	6	9	14		
Classification				*Classification*	
Sugar beet	97	96	98	Sugar beet	97
Weed	91	88	61	Weed	99
Average	94	92	80	Average	98
Spraying effect				*Spraying effect*	
Hit rate	93	94	89	Hit rate	99
Herbicide reduction	68	31	15	Herbicide reduction	26

Table 1, right shows that for perfectly labelled samples, the classifier has an average sample classification success rate of 98%, an expected weed hit rate of 99% and a herbicide reduction of 26% for an average weed density of 37 weed plants/m^2. With the proposed labelling, Table 1 shows that the labelling accuracy is almost insensitive to the weed density. A low increase in accuracy with increasing weed density could be explained by the fact that relatively more weed samples present between the rows (certainly weed) enable to cluster the weed samples more accurately. For the same reason, crop could also be labelled more accurately. Corresponding classification success rates do not differ significantly from the case in which the sample labels are perfectly known. The success rate for the crop samples follows the same tendency as the crop labelling accuracy. However, they show a decrease in recognising the weeds with increasing weed density. Weed hit rates are still acceptable for all weed densities. Herbicide reductions decrease, as expected, with increasing weed density. Due to an increase in the classification error, the herbicide reduction remains significant, even for the higher weed density.

CONCLUSIONS

Existing spectral measurement techniques are far too slow to be integrated into an online intelligent spray apparatus. The spectral measurement technique we implemented combines spectral resolution and spatial sensitivity to a fast and sufficiently accurate crop versus non-crop classifier.

The proposed cluster algorithm can be used to label a set of data samples, collected with the proposed multi-spectral image sensor. Prior row or between-the-row labels that were assigned to each of the samples suffice to eliminate every user-interaction and user-knowledge in collecting and labelling the data set. Based on the labelled data set, a classifier was trained to recognise crop and weed for selective spraying of weeds only. This resulted in acceptable weed hit rates of 89% or higher and significant reductions in herbicide use (15-67%), which, for the simulated weed densities, spot-spraying becomes economically feasible.

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The influence of growth stage of weeds on the glyphosate dose needed

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ABSTRACT

Three distinct growth stages of black nightshade and couch grass were treated with eight different glyphosate rates. Black nightshade was treated at the 3-4, 5-6 and 9-10 leaf stage and couch grass was treated at the 3-4, 5-6 and 7-9 leaf stage. Dose response relationships demonstrated that the ED_{50} for glyphosate was 7, 36 and 130 g ae/ha with black nightshade at the 3-4, 5-6 and 9-10 leaf stages, respectively. The ED_{50} (dose giving 50 % response) with couch grass was on average 18 g ae/ha and was fairly constant at the different growth stages investigated. Relevance of relative growth rate, absolute fresh weight, spray retention and species-dependence is discussed.

INTRODUCTION

Insight into the impact of different weed species and the weed growth stage on herbicide susceptibility may contribute to reduction of application rates (Kudsk, 1989). In this study we investigated the influence of growth stage on the susceptibility for the herbicide glyphosate. The application of glyphosate in glyphosate-resistant crops with a population of weeds at various stages of growth is another argument for this study.

Previous reports indicated that plants at later growth stages are less susceptible to glyphosate (Ahmadi *et al.*, 1980; Mesa-Garcia *et al.*, 1984; Ralphs *et al.*, 1992; Taylor & Oliver, 1997). Broad bean (*Vicia faba* L.) (Mesa-Garcia *et al.*, 1984) and duncecap larkspur (*Delphinium occidentale* S. Wats.) (Ralphs *et al.*, 1992) became less susceptible during and after flowering. The perennial couch grass (*Elytrigia repens* L. Nevski) appeared to be less susceptible at young stages (1-3 leaf) when compared with the 4-7 leaf stages (Rioux *et al.*, 1974; Ivany, 1975). A study on five species of annual morningglory (*Ipomea* spp.) demonstrated that the influence of growth stage on glyphosate efficacy depended on the species (Wehtje and Walker, 1997).

The stage of growth may influence the susceptibility-determining factors like entry of glyphosate into the plant and the distribution in the plant. Young barnyardgrass absorbed more glyphosate and translocated the herbicide more efficiently than older stages (Ahmadi *et al.*, 1980). At the shoot elongation stage, ligustrum (*Ligustrum japonicum* Thunb.) and blue pacific juniper (*Juniperus conferta* Parl.) absorbed more glyphosate than at other stages (Neal *et al.*, 1985). Studies on flax (*Linus usitassimum* L.) (Harvey *et al.*, 1985) and Canada thistle [*Cirsium arvense* (L.)] (Hunter, 1995) indicated that the source-sink relation at the different stages of growth determined the direction of the glyphosate translocation in the plant.

In addition to the obvious demand for entry of glyphosate into the plant and translocation of sufficient amounts to the meristems, we argue that the plant's response, after inhibition of the enzyme EPSP synthase by glyphosate, may also depend on the growth stage. A young rapidly growing plant needs the functioning of the target and will be harmed more by target-inhibition than an older plant growing not at all or slowly. Studies on water-stressed plants provided some evidence for this idea (de Ruiter and Meinen, 1998). In this study we wanted to investigate whether relative growth rate is a suitable tool for fine-tuning of glyphosate application rates. Therefore, we measured the influence of growth stage on glyphosate susceptibility in relation to the growth rate at different stages. To determine accurately the influence of growth stage, we established a dose-response relationship at each growth stage using black nightshade (*Solanum nigrum* L) and the perennial couch grass. We also investigated whether spray retention was affected by growth stage.

METHODS AND MATERIALS

Plant material

Black nightshade and couch grass were grown in 11-cm diam. pots filled with a mixture of sand and humic potting soil (1:2, v/v/). After emergence the black nightshade plants were thinned to one plant per pot. Five one-node segments of couch grass rhizomes were planted and the plants emerged were thinned to three per pot. The plants were grown under the following conditions: additional light (high-pressure mercury lamps, 12 h), 18/12 °C (light on/light off) temperature and 70/80% (light on/light off) relative humidity. The pots were placed on sub-irrigation matting which was wetted daily with water and twice a week with nutrient solution.

Characterization of plant growth

The growth of black nightshade and couch grass plants was monitored during a period of eleven weeks. The first harvest of both species was ten days after emergence and was followed by twenty-one harvests with an intervening period of alternately three and four days. The growth of black nightshade was analyzed by measuring fresh and dry weight of the aerial parts and the roots. The growth of couch grass was analyzed by measuring fresh and dry weight of the aerial parts, the roots and the rhizomes. We also determined per pot (three plants) the number of rhizomes, the length of the rhizomes and the number of buds.

The influence of growth stage on glyphosate efficacy

Black nightshade plants at the 3-4, 6-7 and the 9-10 leaf stage and couch grass at the 3-4, 5-6 and the 7-9 leaf stage were sprayed with glyphosate solutions. In one experiment we also treated black nightshade at the 11-leaf (flowering) and the13-leaf stage (seed-filling). Each week, the growth of a new batch of plants was started such that the different growth stages of one species could be treated on the same day. Prior to treatment four pots were used to characterize the plants at the time of treatment as described above. Another four pots were used to determine the retention of spray solution on the foliage for each stage of growth. The glyphosate solutions contained the monoisopropylamine salt of glyphosate at eight different concentrations and the polyoxyethylene (15) tallow amine surfactant

(Ethomeen T/25) at 2.5 g/litre. The 3-4 leaf and the 6-7 leaf stage of black nightshade were treated with glyphosate at application rates ranging from 1 to 265 g ae/ha. The 7-9 leaf stage and older stages were treated with rates ranging from 1 to 1908 g ae/ha. Couch grass was treated with glyphosate at application rates from 1 to 578 g ae/ha. The glyphosate efficacy was determined by measuring the fresh weight of the aerial parts two weeks (black nightshade) and two or three weeks (couch grass) after treatment. The glyphosate solutions were applied with an air-pressured laboratory track sprayer delivering 400 litres/ha at 303 kPa. Spray solutions used for quantification of retention on the foliage contained the fluorescent dye Na-fluorescein at a concentration of 0.1 g/litre and the surfactant at 2.5 g/litre. Retention of the spray solution was quantified by spectrofluorometry according to Richardson (1984).

Experimental design and data analysis

Period of growth was the variable in the growth experiment. At each of twenty-two time points four pots were taken out for harvest of the plants. Due to a limitation in the number of pots that could be placed in a tray, the pots were distributed over two randomized blocks with each two replicates. One experiment was conducted under the greenhouse conditions as described under plant material and another experiment was conducted under similar conditions in a climate chamber. The mean fresh weights of the aerial parts were subjected to nonlinear regression (Genstat 5) using the equation for the Gompertz curve:

$$y = a + c \exp(-\exp(-b(x-m)))$$

In this equation y is the fresh weight, x is the number of days after emergence, a, b, and c are parameters describing the shape and the position of the curve. The calculation of relative growth (RGR) was based on the equation for growth by using:

$$RGR = (1/y)(dy/dx).$$

Glyphosate efficacy

All pots of one growth stage were placed in one completely randomized block with four replicates in the block. The positions of the blocks were randomized. At least four separate experiments were conducted with each species. The mean fresh weights of the aerial parts were subjected to nonlinear regression (Genstat 5) using the equation:

$$y = a + c/(1 + \exp(-b(x-m))$$

In this equation, y is the fresh weight, x is ln(glyphosate concentration), a is the lower limit at large doses, a + c is the upper limit at zero dose, m is the $\ln ED_{50}$ (ED_{50} is equivalent dose for 50 % response) and b is the slope parameter that determines the slope around the ED_{50}. The $\ln ED_{50}$ values were subjected to analysis of variance.

RESULTS AND DISCUSSION

Growth of black nightshade and couch grass

Growth of black nightshade (Fig. 1A) was monitored until 83 days after emergence and that of couch grass (2A) was monitored until 81 days after emergence.

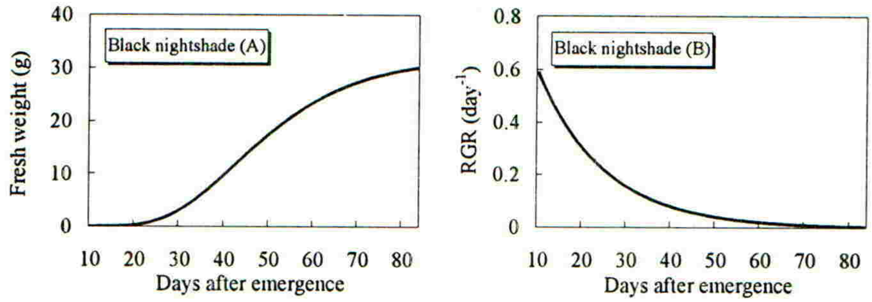

Figure 1. Fitted growth (A) and relative growth (RGR) of black nightshade (aerial parts) grown in the greenhouse.

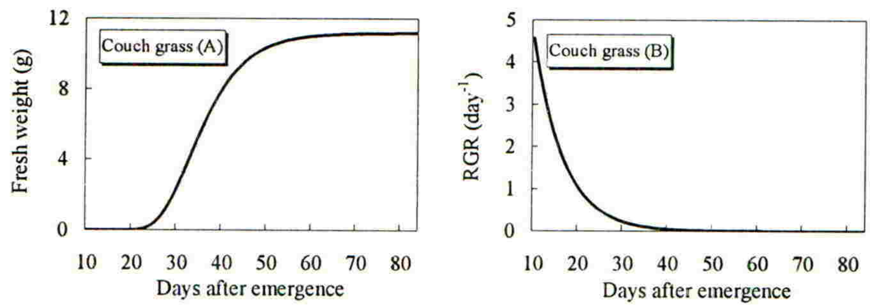

Figure 2. Fitted growth (A) and relative growth (RGR) of couch grass (aerial parts) grown in the greenhouse.

The flowering of black nightshade started around 40 days after emergence and the seed-filling period started around 60 days after emergence. Couch grass did not flower during the growth experiment. Development of rhizomes started from 33 to 36 days after emergence and the number of rhizome buds per pot (three plants) was 80 at the end of the monitoring-period. The RGR of both species was relatively low 40 days after emergence (Figs. 1B and 2B). At the young stage of couch grass, the fitted growth curve diverged somewhat from the pattern in the plot of the fresh weights measured (not shown) and this resulted in unrealistic high values for the RGR between 10 and 20 days after emergence.

Influence of growth stage on susceptibility for glyphosate

Black nightshade became less susceptible at later stages of growth (Table 1) as was shown for other species (Ahmadi et al., 1980; Mesa-Garcia et al., 1984; Ralphs et al., 1992; Taylor & Oliver, 1997). At the flowering stage (49 days after emergence) and the seed filling stage (63 days after emergence) the plants lost their susceptibility almost completely. The limited number of growth stages tested so far (5) do not allow to consider accurately a mathematical relationship between ED_{50} and RGR (Table 1B). There seems to be a clear inverse relationship: ED_{50} increases when RGR (based on aerial parts) decreases.

Table 1. Influence of growth stage on the susceptibility of black nightshade for glyphosate

		ED_{50} (g ae/ha)					
		Experiment					
DAE[1]	Leaves	1	2	3	4	5	Mean[2]
21-22	3-4	6.7	3.7	10.9	4.9	9.1	7 a
28-29	5-6	14.9	10.8	44	10.4	nd	36 b
33-36	9-10	nd	51.1	133.9	86.6	258.4	130 c
49	11					>>[3]	
63	13					>>[3]	

[1] DAE = days after emergence.

[2] Means within one experiment followed by the same letter do not differ at the 5 % probability level (LSD).

[3] Glyphosate at 1908 g ae/ha reduced the fresh weight by less than 20 % of the control plants.

By using the data of the separate experiments we could describe a linear relation between fresh weight on the day of treatment (x) and the ED_{50} (y) as $y=12.3x$ ($R^2=0.75$). The retention of spray solution (y) was influenced by the fresh weight on the day of treatment (x) according to $y=0.7x^2-52x+1021$ ($R^2=0.97$). This means that the retention decreases from 1000 to 100 µl g^{-1} dry wt from the very young stage to the seed filling stage. The retention decreases by 50 % from the first stage to the third stage (from 21 to 36 days after emergence) and we do not think that this explains the substantial increase of ED_{50} (Table 1). The surfactant selected was included for its property to enhance the foliar uptake of glyphosate (de Ruiter 1998). Although foliar uptake is not yet determined at the older stages we suggest that the source-sink relationships in the plant and the RGR rather than the targeting of the herbicide determined the influence of growth stage on glyphosate efficacy. The data indicated that the absolute fresh weight on the day of treatment and RGR of the aerial parts of black nightshade has the potential to serve as an indicator for glyphosate efficacy.

Couch grass demonstrated the same susceptibility for glyphosate at the stages tested (Table 2). We did not find a lower susceptibility at a young stage (3-4 leaf) as mentioned before for the 1-3 leaf stage (Rioux *et al.*, 1974; Ivany, 1975). Difference in growth stage

Table 2. Influence of growth stage on the susceptibility of couch grass for glyphosate.

		ED_{50} (g ae/ha)				
		Experiment				
DAE[1]	Leaves	1	2	3	4	Mean[2]
17-18	3-4	nd	20.9	11.7	10.5x	15.1 a
23-25	5-6	20	28.4	16.7	18.8	21 a
31-37	7-9	22.9	26.2	9.7	10.4	17.3 a

[1] DAE = days after emergence.

[2] Means within one experiment followed by the same letter do not differ at the 5 % probability level (LSD).

and experimental procedures may explain this. Equal susceptibility at older stages was found previously (Ivany, 1975). The level of retention of spray solution varied between 350 and 500 μl g^{-1} dry wt among the separate experiments and was not influenced by growth stage (data not shown). The RGR of the aerial parts was lower at the older stages tested but this had no impact on susceptibility for glyphosate. At the oldest stage tested (33-36 days after emergence, 9-10 leaf stage) the plants just started with the development of new rhizomes. This means that the foliage, although growing at a lower RGR, is an active tissue involved in the translocation of assimilates and a phloem-mobile compound like glyphosate to the rhizomes and the roots. Apparently, RGR of and fresh weight of the aerial parts of couch grass are no suitable parameters for fine-tuning of glyphosate application rates. We suggest that rhizome development and the ratio between aerial parts and the rhizomes may better parameters. We suggest that regrowth from buds is the best and most relevant method to test this.

We conclude that the usefulness of the relative growth rate of the aerial parts and the fresh weight on the day of treatment, as indicators for glyphosate efficacy, is species-dependent. Our data with black nightshade indicate that these parameters are suitable for annual dicots.

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Evaluating site-specific weed control in a maize-soybean rotation system

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ABSTRACT

Targeting weed patches for herbicide application potentially represents cost savings for operators and reduction in environmental herbicide load. An experiment was initiated in a no-till corn field in Ontario, Canada, in 1998 and continued in rotation with no-till soybeans in 1999. Weeds were intensively scouted in a 4 ha area and weed distribution maps were generated for both years. Efficacy of weed control and yield were compared between conventional broadcast treatments and site-specific application treatments. Treatments were applied using a direct injection sprayer. Corn yield in 1998 was identical across all treatments. In 1998 and 1999 there was no difference in the level of weed control between treatments and the percent area sprayed in the site-specific treatments was reduced as much as 26 to 59% in some treatments.

INTRODUCTION

In traditional agricultural weed management situations herbicides are sprayed on the entire field with the assumption that weed distribution is random or uniform throughout the field. However, in most cases weeds are patchy or clustered in distribution (Mortensen & Dieleman, 1997; Cousens & Woolcock, 1997). The concept of site-specific herbicide applications offers the opportunity to reduce the environmental impacts of herbicide use in farming while maintaining efficacy and profitability. In theory, site-specific herbicide applications would only target the areas in the field that have weed patches at densities that would impact on the yield of the crop. Stafford & Miller (1996) have suggested that there would be a 40 to 60% reduction in the amount of herbicide inputs into the environment if site-specific applications were utilised. As well as the potential environmental benefits, site-specific applications would economically optimise the use of herbicides and thus result in a cost reduction for the farmer.

As of yet, there has been very little research done examining if site specific herbicide applications would perform as effectively, with regard to weed control, compared to broadcast herbicide applications. Another important issue relating to site-specific applications that has not been adequately investigated is the effect of targeting weed patches for herbicide applications on patch stability. If patches remained relatively stable in a field from year to year then farmers could use the same weed maps for several years without having to have their fields re-mapped yearly.

The objectives of this research are to monitor the efficacy of site-specific herbicide applications compared to broadcast herbicide applications for weed control and yield, and to monitor the dynamics of weed patches and weed free areas over time.

METHODOLOGY

A commercial no-till field site in a corn-soybean-wheat rotation was chosen for the study. In the spring of 1998, a 100 x 400m portion of the field was flagged on a 6 x 6m grid. Flags were geo-referenced using a GPS and left as semi-permanent markers in the field throughout the summer. In 1998 the field was planted into corn and in 1999 was planted into soybeans. Just prior to the 5^{th} leaf stage of the corn and the 2^{nd} trifoliate stage of the soybeans weed counts were conducted. At each flagged intersection point a 1 x 1m quadrat was laid down on the ground and weeds within the quadrat were identified and counted.

From the weed counts, weed contour maps were developed for the most prevalent species using the GIS program Surfer. Simple point kriging was used as the interpolation method based on the variograms developed in Gstat for each species.

The field was further divided into 16 plot areas of 28 x 85m. The experiment was laid out according to a randomized complete block design with 4 replications and 4 treatments. The same randomization was used from year to year. Each weed contour plot map was divided into management units of 3 x 5m that the sprayer was capable of targeting. Decisions on whether to spray or not were based on the presence of targeted weed species above the threshold density of 1 shoot m^{-2} in any portion of each decision unit. For each plot there were 136 decision units. The broadcast treatment plots were not assessed and the whole plot area was targeted for herbicide application. Depending on the treatment, two or three of the weed density contour maps were overlaid. Once the decisions about what units would be sprayed had been made, prescription maps were created that could be read by the on-sprayer computer.

The direct injection sprayer system (Bennett & Brown, 1999) is equipped with a water tank and a separate container of the herbicide that is to be injected according to the prescription map. The sprayer constantly sprays the carrier and injects the herbicide only for those decision units that have been prescribed for application. Therefore two types of site-specific applications were possible, 1) injection of herbicide for targeted areas only or 2) injection of herbicide for the targeted areas and simultaneous blanket coverage over the entire plot area with another herbicide mixed into the carrier tank.

In 1998 the herbicides sprayed were nicosulfuron/rimsulfuron, flumetsulam/clopyralid/2,4-D and atrazine at 0.10 kg ai/ha, 0.28 kg ai/ha and 1.15 kg ai/ha, respectively. In 1999 the herbicides sprayed were chlorimuron ethyl at 0.009 kg ai/ha and acifluorfen at 0.6 kg ai/ha. Applications were made at the 6^{th} leaf stage of the corn in 1998 and the 2^{nd} trifoliate stage of the soybeans in 1999 according to the treatment lists in tables 1 and 2. Three to four weeks after application, weed counts were conducted on the same 6 x 6m sampling grid. Yield was also collected in the autumn of 1998. Statistical analysis was performed using an ANOVA and means were compared using the LSD test.

Table 1. Herbicides applied and weeds targeted in 1998

Treatment no.	Herbicides	Weeds targeted[a] TAROF	SONAS	EQUIR
1	Flumetsulam/clopyralid/2,4-D	I[b]	I	I
	Atrazine + nicosulfuron rimsulfuron	I	I	I
2	Flumetsulam/clopyralid/2,4-D	BC	BC	BC
	Atrazine + nicosulfuron rimsulfuron	X	I	I
3	Flumetsulam/clopyralid/2,4-D	BC	BC	BC
	Atrazine + nicosulfuron rimsulfuron	I	I	I
4	Flumetsulam/clopyralid/2,4-D	BC	BC	BC
	Atrazine + nicosulfuron rimsulfuron	BC	BC	BC

[a] TAROF: *Taraxacum officinale*, SONAS: *Sonchus asper*, EQUIR: *Equisetum arvense*.
[b] I: herbicides injected for patches above threshold density, X: no injection even if density is above threshold; and BC: broadcast application of the herbicides to the whole plot area.

Table 2. Herbicides applied and weeds targeted in 1999

Treatment no.	Herbicides	Weeds targeted[a] CHEAL	SONAS	EQUIR
1	Chlorimuron +acifluorfen	I	I	I
2	Chlorimuron	BC	BC	BC
	Acifluorfen	I	X	I
3	Acifluorfen	BC	BC	BC
	Chlorimuron	X	I	X
4	Chlorimuron +acifluorfen	BC	BC	BC

[a] CHEAL: *Chenopodium album*, SONAS: *Sonchus asper*, EQUIR: *Equisetum arvense*.
[b] Symbols as per table 1.

RESULTS AND DISCUSSION

The most prevalent weed species found over the two years were field horsetail (*Equisetum arvense*), spiny-annual sowthistle (*Sonchus asper*), common lambsquarters (*Chenopodium album*) and dandelion (*Taraxacum officinale*). Visually the field horsetail patch was quite localized and very dense and this was confirmed by the geostatical analysis. The variogram equation reflected the high spatial correlation with a nugget value of zero and the range of spatial dependence was of 61.54 m . The spiny-annual sowthistle patches ran lengthwise in the field following the direction of the implement traffic and this was reflected in the variogram equations with north/south (N/S) anisotropy. Both spiny-annual sowthistle and common lambsquarters had relatively low nugget values indicating that spatial correlation existed but random variation was also present. Common lambsquarters had a much shorter range of spatial dependence at 6.7 m while spiny-annual sowthistle had a range of 14.33 m. Common lambsquarters was not present at high densities in 1998 and was not targeted. However it was found to be very abundant in this field in 1999 and densities warranted its inclusion in the decision grid. Dandelion was targeted for herbicide application in 1998 but not in 1999. The variogram equation indicated that there was no spatial correlation and therefore was randomly distributed. A preplant application of glyphosate at 900 g ai/ha controlled dandelion in 1999. The variograms derived from counts of field horsetail and spiny-annual sowthistle in 1998 were very similar to those derived from 1999 observations. This suggests that the level of patchiness of a particular weed may remain stable within a field. However no conclusions can be drawn about relative field to field patchiness of a particular weed. As for the stability of a patch in a field over time it seemed to be dependent on the weed type. The field horsetail patch was almost in exactly the same location as the previous year (Figure 1). There was a greater year to year variation in patch location for spiny annual sowthistle (Figure 2).

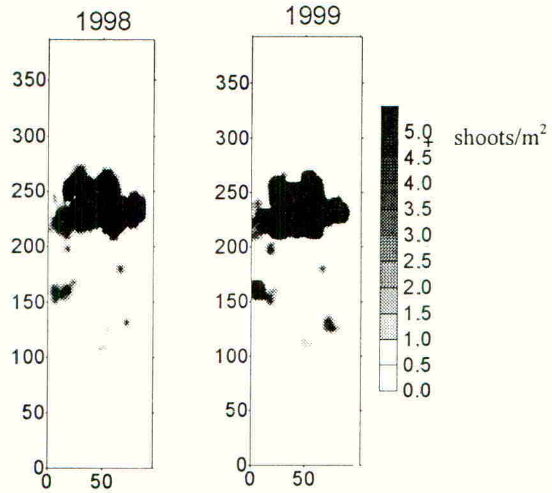

Figure 1. Initial field horsetail maps from 1998 and 1999 for the 4 ha field area. Axes present distances are in meters.

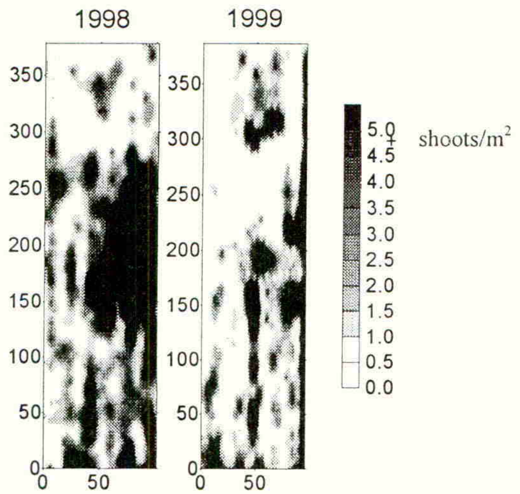

Figure 2. Initial sowthistle maps from 1998 and 1999 for the 4 ha field area. Axes represent distance in meters.

Weed control was assessed by comparing the initial weed counts in each quadrat with the counts for that same quadrat 3 to 4 weeks after application. Regardless of the year, there was no significant difference in weed control between any of the treatments for each species. In 1998, excellent control of spiny-annual sowthistle and field horsetail were obtained with values ranging between 76 to 92% and 86 to 99%, respectively. Control of dandelion ranged between 69 to 80%. In 1999, control of spiny-annual sowthistle ranged between 97 to 99%. Control of lambsquarters and field horsetail was lower which reflects the fact these species are difficult to control with the herbicides used in 1999. Levels of control ranged between 28 to 70% for lambsquarters and 10 to 41% with field horsetail.

There were no differences in yield between any of the treatments in 1998 with values ranging from 9.0 to 9.5 tonnes/ha. There was, therefore, no yield advantage in applying herbicides to the whole field as compared to the site-specific applications. The absence of yield differences among the four treatments is in agreement with the fact that weed control levels were identical.

With these results in mind the next relevant question is whether the actual plot area sprayed was reduced in the site-specific treatments and to what magnitude. In 1998 the actual area sprayed in the site-specific treatment (1) was 26% less than the traditional broadcast treatment (4 in Figure 3). However, the combination site-specific/broadcast treatments (2 and 3) were not different from treatment 4. In 1999, there was no difference in the total area sprayed with site-specific treatment (1) as compared to treatment 4, but the combination site-specific/broadcast treatments (2 and 3) reduced the actual area sprayed by 59 and 50%, respectively. The reductions seen in the combination site-specific/broadcast treatments (2 and 3) are only representing the injection component of the application.

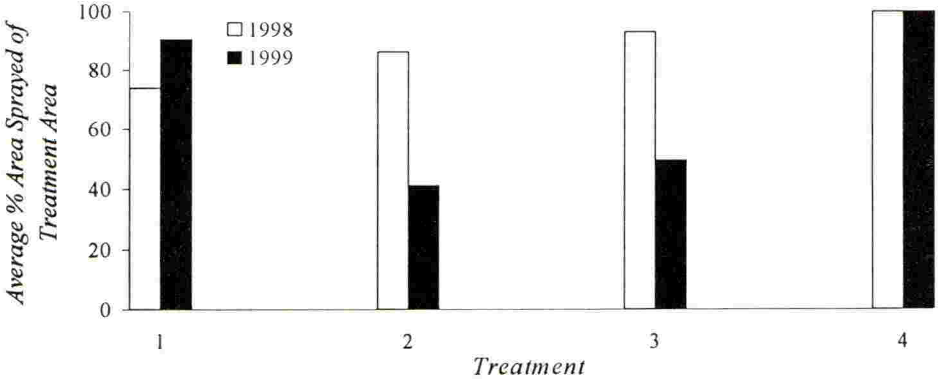

Figure 3. Reduction of area sprayed by using site-specific herbicide applications in both 1998 and 1999 as compared to broadcast.

Site-specific herbicide applications provided encouraging results in both years. The reduction in herbicide inputs would be meaningful economically to a farmer as well as environmentally to the public. However the entire process is in need of refinement. Obviously, in a large field scale situation the intensive sampling method that was used would be time consuming and costly. As technology progresses, better ways of accurately locating weed patches in the field when the weeds are small and within the herbicide application window will be developed. The direct injection sprayer restricted the size of our decision unit. Perhaps a flexible decision unit size would reduce the number of zones that were targeted where only a very small portion of the area was above the threshold density. Moreover, the decision whether to spray an area or not was based on a single criteria for all broadleaf weed species. Realistically, each weed species would have a different impact on the crop based on density, location in the patch (Mortensen & Dieleman) and time of emergence. Leaving an area unsprayed because it did not have weeds above threshold densities may impact the possibility of using the same weed maps over several years. For example in 1998 common lambsquarters was not targeted because it was not above the threshold but in 1999 it was one of the major species in this field. More research into the dynamics of weed patches as well as the impact of site-specific herbicide applications is required if precision weed management is to be a success.

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Methods of weed patch detection in cereal crops

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ABSTRACT

This paper reviews the merits of real-time and map-based systems of weed assessments and discusses the importance of the precision of the map. 'Traditional' mapping based on weed density counts on a regular grid are useful for research purposes but are too expensive for practical on-farm mapping. Visual weed detection systems can already be used to record weeds but tend to be labour intensive and so need improvement to increase their cost-effectiveness. The potential for automatic weed detection is being explored by a number of research teams. Reflectance techniques can already be used to detect weeds in uncropped areas and between crop rows in crops sown with wide row spacings. However, although progress is being made with experimental systems, commercially viable methods to detect weeds within narrow row crops are not yet available. Systems involving combinations of reflectance, colour and leaf shape are in development and some are being tested in the field. There has to be a compromise between the cost of mapping and the need for the map to reflect the distribution of weeds. Thus fine maps are preferred to the cheaper coarse maps since some of the advantages of the technique will be lost if sample grids are too coarse.

INTRODUCTION

The development of the mechanical and electronic components of spatially selective weed control (patch spraying) is proceeding apace, in step with yield mapping and spatially variable fertiliser application. A number of manufacturers are developing variable rate sprayers with the capability to patch spray weeds. Control systems such as the AGCO Fieldstar have the potential to control such sprayers and Global Positioning Systems (GPS) are able to locate the sprayer's position in the field with reasonable reliability. A recent (1998) survey of maize (corn) growers in the mid-west USA reported by Robert (1999) indicated that 29% of all growers were field mapping in some way and 14% were yield monitoring. In Europe uptake of this technology is also growing and the number of combine harvesters with a yield mapping capability is increasing. However, the current low prices for grain may be slowing the uptake of this new technology. Most emphasis, to date, has been put on spatially variable fertiliser application. The use of this technology to control weeds on spatially selective basis is not so far advanced. One of the main reasons for this is the difficulty of resolving the question, how do you assess the weeds? The answer to this question has considerable implications for the economic success of the technique of patch spraying weeds, as expensive assessments could nullify the cost savings arising from the reductions in herbicide use.

There are three basic questions that have to be answered.

1) How do you record the distribution of weeds? Can a visual (human) method be used or should assessment be automated?

2) Should the assessment be based on creation of a weed distribution map for subsequent use in controlling the sprayer or should the weed mapping and treatment be in one operation (real-time detection)?
3) How precise does the map have to be?

In the following sections we will review the current state of development of the various techniques that can be used to assess weeds. It is clear that some potential users believe that the only practical way forward is to combine detection and herbicide application in one operation, with real-time detection of weeds. However, we believe that there are also advantages to map-based systems, where the weeds are assessed either automatically or visually prior to application and the herbicide application is controlled by an application map derived from the weed map. The former has the advantage of immediacy, whilst the latter offers the potential for consideration of herbicide choice and the need for buffers, prior to treatment. Many of the mapping issues described below relate to both real-time and mapped based application systems.

MANUAL WEED DETECTION TECHNIQUES

Assessment systems that involve some form of human assessment of weed distribution normally require the production of a map which can then be used to control the herbicide application. Except at a very primitive level, real-time detection and treatment is not possible in such systems. It is possible for farmers, when treating weeds late in the season, to switch spray booms on and off as they travel across fields, identifying primary weed patches at the same time. However, this is a very coarse approach to patch treatment.

Density assessments from GPS located quadrats

Most of the research programmes concerned with the potential of spatial treatment of weeds have been based on grids of quadrats, located either with GPS or by measurement. The counts generated by these quadrats have then been converted to weed contour maps by kriging or a related method. This is a satisfactory method for research purposes, although the issue of the optimum grid size is still to be resolved (see below). The practical field mapping and spatial treatment programmes in Germany (Gerhards *et al.*, 1997; Häusler *et al.*, 1998), Denmark (Heisel *et al.*, 1999) and Canada (Goudy *et al.*, 1999) all use grids of various sizes to determine the spatial distribution of weeds. This technique is perfectly acceptable for research purposes and is an invaluable tool for 'ground truthing' assessments made from aerial images or from other automated detection methods (see Rew *et al.*, 1999). It is, however, far too labour intensive for practical farm use.

Ground-based visual detection

This technique is based on a human observer travelling in a regular pattern over the fields to be mapped, visually recording the presence and absence of the target species. The operator's position is geo-referenced using a GPS system and the resultant map can be used subsequently to control herbicide treatments. It is possible to map weeds using this technique from an all-terrain vehicle (ATV), whilst the crop is small (e.g. in winter in autumn sown crops), providing an opportunity for pre-treatment mapping. It is also possible to map certain species during summer from a tractor or at harvest from a combine harvester, recording areas of poor control, which will highlight those areas where seed return will be highest and where most weeds will be expected in the following year. It is possible to record presence absence and/or to quantify infestations into low/high. Such a technique was tested extensively by Rew in the UK, (Rew *et al.*, 1996; Lutman *et al.*, 1998) but she used three people (a driver and two assessors) to map weeds, which is too extravagant with labour to be commercially viable. The mapped species tend to be the more aggressive ones that inevitably are more visible. This is an advantage, as it is these species that are the most appropriate targets for spatially selective treatments, and are targeted with specific rather than broad-spectrum treatments, which tend to be expensive (e.g. control of *Alopecurus myosuroides* (black-grass) and *Galium aparine* (cleavers) in UK winter cereals). Faechner & Hall (1999) have reported a two-person system ATV-based method for mapping *Cirsium arvense* (creeping thistle) and *Sonchus sp.* (sow-thistle) in oilseed rape (canola). They were able to map presence and absence of the thistles (at 20 m intervals) in a 28 ha field in 1 h. Colliver *et al.* (1996) have compared quadrat counts of *Avena fatua* (wild-oats) with observations of pre-harvest and at-harvest panicle distributions. Quadrat counts were most time consuming but were most accurate.

Our own studies this year have explored the practicality of single-person mapping from an ATV, a tractor or from a combine harvester. It is possible to map in this way but current mapping hardware needs to be modified for single person operation. Progress is being made with voice-recognition software so that the tractor/combine driver mapping weeds has only to speak into a microphone (M E R Paice, pers. comm., 1999). Preliminary estimates from ATV mapping based on 6 m intervals, and tractor mapping based on 12 m intervals, indicate that it is possible to map at 2-4 ha/h from an ATV and 3-6 ha/h from a tractor, depending on field length and number of turns (N H Perry, unpubl. obs.). Combine mapping is inevitably slower than tractor mapping, but provided the driver is doing the mapping, this is not a problem. Combine mapping has the advantage that the width of view (header width) would be less than with other forms of mapping, providing a more accurate weed map. However only certain weeds, such as *A. fatua, C. arvense* and *Elymus repens* (common couch) will be visible at this time. Our work suggests that such visual methods are practical for commercial farmers or their crop protection advisors, provided maps do not have to be created every year.

AUTOMATED WEED DETECTION TECHNIQUES

Automated detection systems offer the possibility of both creating weed maps that can be used to control subsequent herbicide treatment, or could be connected directly to the sprayer providing a mechanism for real-time detection and treatment.

Satellite and airborne remote sensing

Both these remote sensing techniques depend on automated detection, with sensors recording multispectral differences in the landscape. These images can then be manipulated, if necessary, to highlight the specific aspects of the image that are of interest, to create a treatment map for subsequent herbicide application.

Satellite mapping

The accuracy of satellite-based mapping has improved over the last 10 years and such maps are widely used to evaluate changes in larger scale features of the landscape. Their potential to map weeds has been explored by several research teams, mostly concentrating on extensive agriculture or weed problems of semi-natural and natural habitats. For example, Anderson *et al.* (1993) report the use of satellite images to map *Ericamera austrotexana* (false broomrape) in Texas rangelands. At certain times of the year satellites could be used to detect major stands of this weed and produce geo-referenced maps. In this survey each cell (pixel) was 20 m^2. This technique has limited relevance to weeds in arable fields, as satellites still have relatively coarse spatial resolution and only a limited range of spectral bands. Consequently, the technique is more suited to mapping invasive weeds that inundate large areas, such as bracken in the UK, than for mapping weeds in arable fields.

Aircraft based mapping

A number of researchers concerned with extensive arable agriculture have investigated the potential for aircraft mounted spectral reflectance meters to detect and locate weed patches. A recent paper by Rew *et al.* (1999) reports the results of airborne mapping of *A. fatua* in a field of triticale in Australia. Multispectral images were collected, with a pixel resolution of 1m and the maps created were compared with maps from quadrat counts on a 7 x 7 m grid. The multispectral images detected high infestation areas but could not detect those where *A. fatua* density was below 20 plants/m^2. A similar study on flowering infestations of *Hieracium pratense* (yellow hawkweed) in meadows of Idaho, also used multispectral images collected from an aircraft (Carson *et al.*, 1995). They too achieved 1m ground resolutions. However, as with the Rew study, the imaging system was unable to detect low infestations of the weed (less than 20% cover).

At present, this technology does not provide adequate precision for the mapping of weed infestations in arable fields, especially where weeds occur at relatively low, but still damaging, levels of infestation. Improvements in sensor technology and in ground resolution down to sub metre pixel sizes may result in more practical systems being developed in the future (McGowan, 1998).

Vehicle and hand-held systems

Ground-based detectors that use red and infra-red reflectance to detect green weeds against a brown soil background, have been in existence for more than 15 years (Haggar *et al.*, 1983). Commercial machines have been developed for treatment of weeds pre-drilling, pre-harvest, post-harvest and in fallows, and for application between the rows of crops, such as maize and soybeans sown with wide row spacings (Felton, 1995; Blackshaw *et al.*, 1998; Hanks & Beck, 1998). Research on reflectance characteristics of the visual and infra-red spectra has shown that individual plant species differ in their reflectance characteristics at certain wavelengths. Consequently, it may be possible to utilise such differences to develop in-crop methods to identify weeds. However, changes in sunlight, in plant age and in physiological conditions all alter reflectance characteristics, making reliable distinction between species hard to achieve. More recent research has attempted to improve reliability, with some success. Vrindts *et al.* (1999) reported some progress with the technique when they compared reflectance ratios of six specific wavelengths on nine different species and were able to discriminate between sugar beet and maize and weeds with a 99% level of accuracy. However, this work was done with plants in containers and needs to be validated under more variable field conditions. The research by Feyaerts *et al.* (1999), reported at this conference, continues the investigations of the potential for multi-spectral reflectance to identify the presence of weeds in crops.

An alternative approach to exploit reflectance has also been investigated (Christensen, 1993). This assumes that the crop had a uniform green area and consequently it is possible to calibrate a reflectance meter on weed free areas of the crop. The presence of weeds would result in a change in reflectance from the background level. This technique will not identify species but will indicate areas of the field that have high and low levels of weed infestations. However, it has not been very successful because of spatial variability in crop cover.

Image-based systems

Because of the difficulties of detecting weeds within crops using spectral reflectance, a number of researchers have been exploring the potential for using images from digital cameras to detect weeds. There are a number of problems. Detection systems have difficulty discriminating between species when the leaves overlap and the computing time to achieve identification of species is appreciable, making fast real-time detection difficult. Andreasen *et al.* (1997) have investigated the potential for integrating optical coloured images. Some discrimination was possible. Research by Gerhards (Gerhards *et al.*, 1998) has made progress using a digital camera and computer system to identify plant species from their outline. A similar system in Australia uses colour and shape to identify *Chondrilla juncea* (skeleton weed) in wheat and lupin stubbles (Robbins, 1998). The prototype machines were able to travel at 12 kph, whilst still achieving 95% detection rates. Both these two examples use shrouded cameras and artificial illumination to create even lighting conditions. Effective visual detection may need to combine data relating to geometrical, optical and mechanical properties of the species to be identified. The work of Chapron *et al.* (1999a) has attempted to identify weed seedlings in maize using a combination of geometric and colour attributes of the plants and has given encouraging results, even where leaves overlap. Chapron and his colleagues have also been exploring the potential for using 3D images to enhance detection, as this technique incorporates differences in heights of different species (Chapron *et al.*, 1999b). Only the Robbins project has reached the stage of extensive field validation, although the Gerhards detector has also been tested in the field.

The aim of all the research on automated detection is to develop accurate and speedy methods for the field detection of weed species within narrow-row crops. Progress is being made but although it is possible to detect weeds in wide row crops or in fallows, it is not yet possible to detect weeds in cereals, for example, reliably and quickly using automated techniques. It seems likely that successful systems will require computers to integrate information primarily on plant colour and plant shape to create reliable detection methods

Mapping Intensity and Accuracy of Maps

There has to be a compromise between intensity of sampling/detection that is required to create an accurate weed map and the time and equipment required to do the work. This is most clearly shown in the grid sampling for weed density, where researchers have used very different grid sizes to detect patches. For example, Mortensen in the USA has generally used 7 m grids (Johnson *et al.*, 1996), Christensen in Denmark 24 m (Christensen & Heisel, 1998) and Häusler in Germany 30 and 50 m (Häusler *et al.*, 1998). The coarser the grid the less is the precision, the greater the percentage of the field that appears infested and the lower the potential reduction in herbicide use. The early work done in the UK was based on maps using 2 x 1 m resolution and calculations were done to assess the consequences of increasing grid size to 6 x 1 m. This increased the area treated by approximately 10% (Rew *et al.*, 1997). The potential reductions in herbicide use depends on the aggregation of the species concerned, the size of the assessment grid and the flexibility in the sprayer, as to the minimum area that can be treated. There is a direct mathematical relationship between the grid size, the aggregated nature of the distribution of the weeds and the percentage of the field that is infested (Wallinga, 1995). For example, in a patchy field with a 10 x 10 m assessment grid, 50% of the field appeared infested but if the grid was reduced to 4.6 x 4.6 m only 25% of the field appeared weedy. Weed assessments based on large grid sizes that are relatively cheap to produce may fail to deliver optimum savings in herbicide use.

Automated detection systems have similar problems to grid samples, as although detection in a forward direction can be continuous, the sprayer may only be equipped with one or two expensive detectors. This will result in a grid that could be 1 x 6 m or even 1 x 24 m, if a wide sprayer was only equipped with one detector. Ideally, each boom section should have its own detector. The same problem arises with visual weed assessment from the tractor. Although the operator will be assessing continuously in a forward direction, he/she will only be able to detect weeds to the left or to the right of the tractor and thus will be constrained by the width of the tramlines and the width of the sprayer. Thus mapping from a 24 m sprayer would result in grid sizes of 1 x 12 m. This can be overcome with maps created from a combine harvester or ATV, where the grid width of the former is the header width of the harvester (circa 6 m) and that of the latter could be 1 x 6 m, as the ATV can be driven between tramlines to create a smaller grid size.

CONCLUSIONS

From discussions we have had in recent months in the UK, and presentations at the recent Precision Agriculture Conference in Odense (Stafford, 1999), it seems clear to us that for 'in crop' weed assessment there is currently no commercial alternative to manual weed assessments to create weed maps. Reflectance techniques are already commercialised for applications of herbicides in fallow and other non-cropped areas and in crops grown on wide rows, where the detector is distinguishing between green plants against a brown background. At the moment, automated detection is not an option for commercial use in patch spray systems, as the technology is not yet able to detect green weeds in a green crop. There are some exciting developments involving detection based on combinations of reflectance at a range of different wavelengths, colour and leaf shape, but as yet, such techniques are still at the experimental stage. If manual visual assessment is to be used, it needs to be a single person operation, preferably with the potential for the vehicle driver to map weeds whilst doing another operation. This could be possible with voice recognition software or with simple combinations of toggle switches. The final crucial issue is that we believe that to optimise the technique weed maps need to be created with relatively small grid sizes. It is our belief that grids of 6 x 6 m should be the maximum size, otherwise too much of the potential of the technology is discarded by the coarseness of the grid.

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