SESSION 3A

WEED CONTROL IN CEREALS

Chairman	MR M ASKEW *Central Science Laboratory, York, UK*
Session Organiser	MR M LAINSBURY *Morley Research Centre, Wymondham, UK*
Papers	3A-1 to 3A-6

OVERVIEW OF PROTOPORPHYRINOGEN OXIDASE-INHIBITING HERBICIDES

F E DAYAN and S O DUKE

United States Department of Agriculture, Agricultural Research Service, Natural Products Utilization Research Unit, National Center for the Development of Natural Products, P. O. Box 8048, University, MS 38677, U.S.A.

ABSTRACT

Herbicides inhibiting protoporphyrinogen oxidase (Protox) have been commercialized for more than 30 years, although their molecular site of action remained unknown until 1989. The patent literature indicates that there are thousands of compounds, representing numerous chemical classes, with this mode of action. The most active Protox inhibitors apparently compete for the substrate-binding site of Protox, mimicking portions of the protoporphyrinogen molecule. Light is required for the development of injury, with symptoms becoming visible within a few hours of application. The relationship between activity in the field and the mechanism of action of these compounds will be discussed. Most Protox-inhibiting herbicides are usually applied post-emergence and have broad spectrum weed control. However, more recent commercial Protox inhibitors are extending their use to new crops and to pre-emergence applications. Still, as a herbicide family, their overall impact on the agrochemical market has been limited to a few major crops due to their relatively narrow selectivity. Future use may increase because weeds have not evolved resistance to these herbicides and high levels of crop resistance may be imparted by genetic engineering. Toxicological issues will be addressed, even though these compounds are not considered to be of significant toxicological risk.

INTRODUCTION

Nitrofen, a diphenyl ether, was introduced on the agrochemical market more than 30 years ago. Although its mode of action remained unknown during most of its agrochemical use, this compound was, in fact, the first Protox-inhibiting herbicide to be commercialized. Since then, a large number of experimental Protox-inhibiting molecules have been synthesized (Anderson *et al.*, 1994; Reddy *et al.*, 1997). However, relatively few of these compounds have been commercialized because of their narrow crop selectivity. Commercial Protox inhibitors can be categorized in three broad chemical groups: the diphenyl ethers (*e.g.*, acifluorfen), the phenyl heterocycles such as the oxadiazoles (*e.g.*, oxadiazon), and the heterocyclic phenylimides (*e.g.*, flumiclorac) (Figure 1) (reviewed by Anderson *et al.*, 1994; Reddy *et al.*, 1997).

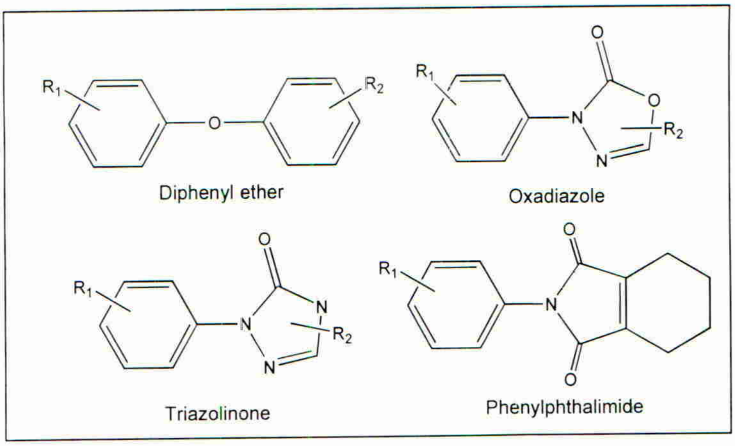


Figure 1. Structural characteristics of several Protox-inhibiting classes of herbicides

Most Protox-inhibiting herbicides have broad weed spectra that often control both monocotyledonous and dicotyledonous weeds. They are used primarily on soybean, though some of these herbicides are suitable for use on other crops (Table 1). Compounds with greater selectivity for cereals and small grains (bifenox and fluoroglycofen) are currently not available in the U.S. market. Protox-inhibiting herbicides are almost exclusively used as foliar-applied materials, and they have little pre-emergence activity. However, more recently discovered structures such as sulfentrazone have excellent pre-emergence activity (Table 1) (Theodoridis *et al.*, 1992). The most active of these herbicides can be applied at rates as low as 1 g per hectare. The growing understanding of the mechanisms of action and resistance to these unique herbicides may broaden their use to other agrochemical markets.

Table 1. Protoporphyrinogen oxidase-inhibiting herbicides commercially available[a].

Common Name	U. S. Trade Name	Main Crop	Application b	Primary Source
Acifluorfen	Blazer®	Soybean, peanut and rice	POST	BASF
Bifenox	Foxpro®	Small grain	PRE/POST	Rhône-Poulenc
Flumiclorac	Resource®	Soybean and corn	PRE/POST	Valent
Fluoroglycofen	Complete®	Cereal crops	POST	Rohm and Haas
Fomesafen	Reflex®	Soybean	POST	Zeneca
Lactofen	Cobra®	Soybean	POST	Valent
Oxadiazon	Ronstar®	Grasses and Ornamentals	POST	Rhône-Poulenc
Oxyfluorfen	Goal®	Vegetable crops	PRE/POST	Rohm and Haas
Sulfentrazone	Authority®	Soybean, sugarcane, tobacco	PRE	FMC Corporation

[a]Information from the WSSA Herbicide Handbook and FMC technical bulletin (see references); [b]PRE = pre-emergence applied; POST = post-emergence applied.

To date, there is only one phytotoxin of natural origin known to inhibit Protox. Cyperin, which was isolated from a several weed fungal pathogens (Weber & Gloer, 1988; Striele *et al.*, 1991; Venkaltsubbaiah *et al.*, 1992), is a diphenyl ether that resembles many commercially available Protox inhibitors (Figure 1). However, its I_{50} value (concentration required for 50% inhibition) was high (60µM) (Harrington *et al.*, 1995), relative to commercial inhibitors. The least active commercial Protox inhibitor has an I_{50} value 1 µM. This high I_{50} value means that other molecular targets may be involved in the mode of action of this natural product. Finally, several commercial herbicides with structural similarities to Protox-inhibiting diphenyl ethers are used for weed control in cereals (*e.g.*, diclofop), but their primary mode of action is not inhibition of Protox. Instead, these compounds inhibit fatty acid synthesis at the level of acetyl-CoA carboxylase (ACCase). Recent comprehensive reviews and books on several aspects of Protox-inhibiting herbicides are available (Duke *et al.*, 1991, Duke & Rebeiz, 1994, Scalla & Matringe, 1994, Dayan & Duke, 1997, and Reddy *et al.*, 1997).

FATE IN THE ENVIRONMENT

Protox inhibitors are not known to be a threat to the environment. The principal form of degradation is associated with microbial activity, though some of these herbicides (*e.g.*, diphenyl ethers) are also susceptible to photodegradation (Table 2). The half-life of this class of herbicides vary greatly and is affected by soil quality. Half-life can be very short (*i.e.*, less than a week for lactofen) but can be as long as 280 days (*e.g.* sulfentrazone) (Table 2).

Table 2. Fate of Protoporphyrinogen Oxidase-inhibiting Herbicides in the Environment[a].

Common Name	Sorption (K_{oc}, mL/g)	Degradation	Mobility	Volatilization	Half-life (days)
Acifluorfen	113	photo/microbiol.	negligible	negligible	14-60
Bifenox	10,000	microbiol.	significant	negligible	7-14
Flumiclorac	strong	photo/hydrol.	negligible	negligible	1-6
Fluoroglycofen	1,364	photo/microbiol.	moderate	negligible	7-21
Fomesafen	60	photo	moderate	negligible	100
Lactofen	10,000	microbiol.	negligible	negligible	3-7
Oxadiazon	3,200	not available	low	negligible	60
Oxyfluorfen	100,000	photo/microbiol.	negligible/low	low	30-40
Sulfentrazone	160-192*	microbiol.	moderate	negligible	110-280

[a] Information from the WSSA Herbicide Handbook and FMC technical bulletin (see references); *Reddy, K. N., Locke, M. A., and Gaston, L. A., 1997, personal communication.

Not surprisingly, some limitations on crop rotation are required with the more persistent Protox inhibitors (*e.g.*, fomesafen and sulfentrazone). Nevertheless, the excellent, broad spectrum pre-emergence activity associated with greater soil persistence of sulfentrazone, relative to other Protox-inhibiting herbicide, makes this herbicide unique in its class for the moment. No significant limitation on crop rotations have been associated with foliar-applied Protox inhibitors. As a group, the relatively high soil adsorption combined with rapid microbial degradation makes Protox-inhibiting herbicides not readily susceptible to leaching in the soil. However, leaching may be of concern with bifenox. Also, soil quality may affect leaching of fluoroglycofen, and metabolites of lactofen may be highly mobile in soil. None of these compounds have volatilization problems (vapor pressure lower than 10^{-7} mm Hg at 25°C), and are not expected to cause drift-related injury to non-target crops.

MODE OF ACTION OF PROTOX-INHIBITING HERBICIDES

In spite of the extensive agrochemical use of these herbicides, their mode of action eluded scientists for many years. Indeed, the exact site of inhibition and mechanism of action were discovered nearly two decades after the first Protox inhibitor was commercially introduced in 1969. Matringe & Scalla (1988) demonstrated that the chlorophyll precursor protoporphyrin IX (Proto) accumulated in acifluorfen-treated plant tissues. The following year, they reported that this abnormal accumulation was in response to inhibition of Protox, the enzyme responsible for its synthesis (Matringe *et al.*, 1989). The apparent paradox of inhibition of an enzyme leading to the accumulation of its catalytic product is explained by altered compartmentation of porphyrin intermediates (Lee et al., 1993). Because of the photodynamic nature of the intermediates involved in the porphyrin pathway, the carbon flow is tightly regulated. Cytotoxic intermediates like Proto do not accumulate. They are rapidly converted to chlorophylls or chlorophyll intermediates. Reduction of the carbon flow through the porphyrin pathway by inhibiting Protox induces an uncontrolled accumulation of Protogen. This colorless and photodynamically inactive intermediate leaks out of the chloroplast outer membrane into the cytoplasm. In this environment, Protogen is converted into the highly photodynamic Proto. This conversion can occur spontaneously in light, but is also enzymatically catalyzed by herbicide-insensitive plasma membrane Protox (Lee *et al.*, 1993). In the presence of light, this photosensitized Proto generates highly reactive oxygen radicals that induce lipid peroxidation of the relatively unprotected plasma membrane (Devine *et al.*, 1993) (Refer to figure 3 for an illustration of the mode of action).

Inhibition of Protox as a mechanism of herbicide action is efficient for several reasons. First, the toxicity is not directly dependent upon the level of inhibition of the pathway since the phytotoxic response arises from the accumulation of Proto. So, while the net chlorophyll synthesis may not be greatly affected by a partial inhibition of Protox, plants can be exposed to cytotoxic levels of Proto accumulation. Second, there is little substrate competition with the herbicide because inhibition of Protox causes the substrate to be lost to the cytoplasm.

A large number of potent Protox inhibitors of varying structures exists. However, they apparently all compete for the same site on the enzyme, suggesting that the binding pocket may be very promiscuous. Herbicidal Protox inhibitors apparently mimic portions of the Protogen molecule (Figure 2). The best Protox inhibitors most closely approximate the geometric shape and electronic characteristics of one-half of the Protogen molecule. However, to our knowledge, no Protox inhibitors have been designed by attempts to mimic portions of the Protogen molecule. Quantitative structure-activity relationship (QSAR) analyses have been somewhat successful in predicting the herbicidal activities of these compounds (Nandihalli *et al.*, 1992; Reddy *et al.*, 1995; Reddy *et al.*, 1997). However, equations derived from one set of compounds may not predict the activity of structurally different groups of herbicides, nor of inactive stereoisomers within the set from which the predictive equations were derived. The major limitation in QSAR work is that the 3-D conformation of Protox has not been determined. Therefore, the topography of the binding pocket and conformational changes occurring during the binding, and at each step of the oxidation of Protogen to Proto, as well as during binding of the herbicide, are unknown. Plant Protox has recently been cloned and its sequence determined (Ward & Volrath, 1995).

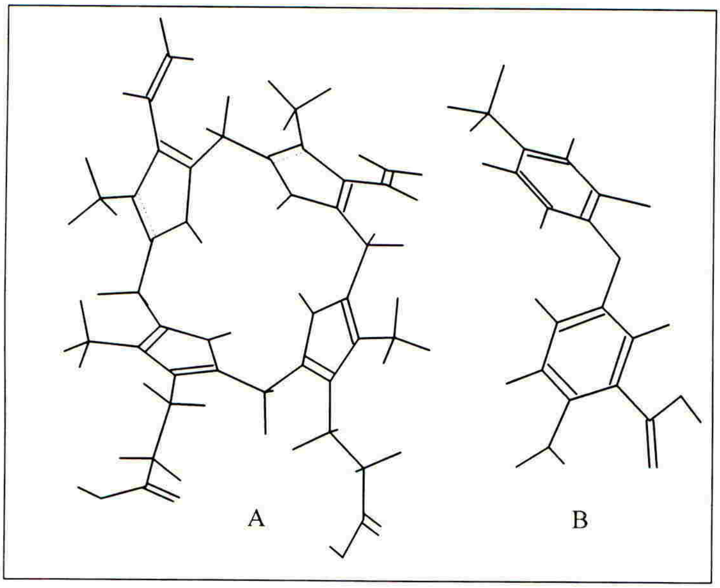


Figure 2. Three-dimensional optimized structures of (A) Protogen and (B) acifluorfen

The forthcoming determination of the 3-D conformation of the binding pocket may enable rational design of new, more active herbicides.

MECHANISMS OF RESISTANCE

Plants have several mechanisms of resistance to herbicides. The most common involve hindered uptake and translocation, rapid metabolic degradation, and/or resistance at the molecular site. However, the complicated mode of action of Protox-inhibitors provides several more unusual sites for possible herbicide resistance (Figure 3).

Reduced uptake and translocation of Protox-inhibiting herbicides through the shoots may account for the resistance of some species (Matsumoto *et al.*, 1994) but does not play a major role in resistance to those that are soil-applied (Dayan *et al.*, 1996, 1997a,b). On the other hand, metabolic degradation of Protox inhibitors seems to plays a key role in crop tolerance to these herbicides. Resistance of soybean to acifluorfen and two phenyl triazolinones is due primarily to rapid metabolic degradation of the herbicides (Frear *et al.*, 1983; Dayan *et al.*, 1997a,b). However, these herbicides act so rapidly that metabolic degradation does not provide a large margin for error, and some crop damage, often referred to as "bronzing", is common. This might be a significant factor with those herbicides that have longer soil persistence.

There are no cases of natural resistance in whole plants associated with herbicide-insensitive chloroplastic Protox. Nevertheless, herbicide-resistant Protox has been isolated from tobacco and soybean cell cultures (Pornprom *et al.*, 1994). However, whole plants have not been regenerated from these cell lines.

Rice appears to be more tolerant to the oxidative stress induced by Protox inhibitors relative to the targeted weeds (Matsumoto *et al.*, 1994). We have reported that a similar mechanism may be involved in the differential sensitivity of soybean cultivars to sulfentrazone (Dayan *et al.*, 1997b). Other species (*e.g.*, mustards) and older tissues of some species that are sensitive in the seedling stage are apparently resistant due to enzymatic degradation of Protogen to non-toxic compounds (Jacobs *et al.*, 1996).

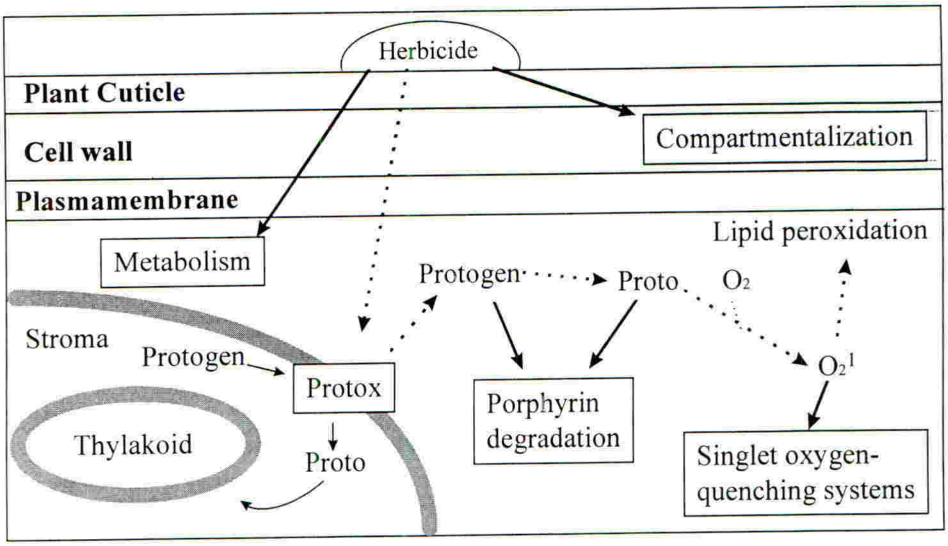


Figure 3. Schematic of possible mechanisms of resistance to Protox-inhibiting herbicides. Mode of action sequence is shown as dotted lines and possible mechanisms of resistance are in boxes (see text for description). Adapted from Duke et al., 1997.

The complex mechanism of action of Protox inhibitors provides several potential mechanisms for evolved resistance in weeds (Figure 3). Yet, no cases of evolved resistance have been verified. This could be due, in part, to the relatively short-lived selection pressure of these fast-acting foliar-applied herbicides. However, the recent development of more persistent soil-active Protox inhibitors will increase the selection pressure, increasing the probability of the evolution of resistance.

TOXICOLOGICAL CONSIDERATIONS

Protox inhibitor herbicides have passed toxicological evaluations prior to registration. These compounds have little acute toxicity and, with the exception of oxyfluorfen and sulfentrazone, have no teratogenic or mutagenic activity (Table 3). However, most of the evaluations were made before the exact site of action of these molecules was discovered. Protox is a key enzyme in both heme and chlorophylls biosynthetic pathways. Consequently, the sensitivity of animal mitochondrial Protox (location of heme biosynthesis) is of concern. Mammalian Protox is as sensitive to Protox-inhibiting herbicides as chloroplastic Protox (Scalla & Matringe, 1994). These compounds can cause greatly elevated levels of porphyrins in animals administered with oral doses of these compounds (Krijt *et al.*, 1994). However, these herbicides are either not readily absorbed by the body and/or are rapidly degraded by metabolism (Hunt *et al.*, 1977; Alder *et al.*, 1977; Leung *et al.*, 1991). Thus, relatively high doses of herbicides are required to elicit an effect, and porphyrin levels return to normal within days after withdrawal of the herbicide.

Table 3. Toxicity of Protoporphyrinogen Oxidase-inhibiting Herbicides[a].

Common Name	Skin sensitization[b]	Oral LD_{50}[c] mg/kg	Teratogenicity[d] mg/kg/d	Mutagenicity[e]
Acifluorfen	none	1540	not available	negative
Bifenox	n/a	>5000	none at 200	n/a
Flumiclorac	none	>5000	> 1500	negative
Fluoroglycofen	none	1500	not teratogenic	negative
Fomesafen	none	> 1200	not available	n/a
Lactofen	none	>5000	not teratogenic	negative
Oxadiazon	none	> 5000	not available	n/a
Oxyfluorfen	none	> 5000	toxic at 120	positive/negative
Sulfentrazone	none	>2000	25	negative

[a]Information from the WSSA Herbicide Handbook and FMC technical bulletin (see references); [b]Guinea pig; [c]rat; [d]rabbit; [e]Ames test; n/a = not available.

In healthy individuals, these compounds are not considered to be of significant toxicological risk due to their effects on porphyrin metabolism. To date, no health problems have been associated with human consumption of crops treated with these compounds (Duke & Rebeiz, 1994).

Kritj, J; Vokurda, M; Sanitrák, J; Janousek, V (1994) Effect of portoporphyrinogen oxidase inhibition on mammalian porphyrin metabolism. *American Chemical Society Symposium Series.* **559**, 247-254.

Lee, H J; Duke, M V; Duke, S O (1993) Cellular localization of protoporphyrinogen-oxidizing activities of etiolated barley (*Hordeum vulgare* L.) leaves. *Plant Physiology.* **102**, 881-889.

Leung, L Y; Lyga, J W; Robinson, R A (1991) Metabolism and distribution of the experimental triazolinone herbicide sulfentrazone in the rat, goat and hen. *Journal of Agricultural and Food Chemistry.* **39**, 1509-1514.

Matringe, M; Scalla, R (1988) Effects of acifluorfen-methyl on cucumber cotyledons: Protoporphyrin accumulation. *Pesticide Biochemistry and Physiology.* **32**, 164-168.

Matringe, M; Camadro, J-M; Labbe, P; Scalla, R (1989) Protoporphyrinogen oxidase as a molecular target for diphenyl ether herbicides. *Biochemistry Journal.* **260**, 231-235.

Matsumoto, H; Lee, J J; Ishizuka, K (1994) Variation in crop response to protoporphyrinogen oxidase inhibitors. *American Chemical Society Symposium Series.***559**, 120-132.

Nandihalli, U B; Duke, M V; Duke, S O (1992) Quantitative structure-activity relationships of protoporphyrinogen oxidase-inhibiting diphenyl ether herbicides. *Pesticide Biochemistry and Physiology.* **43**, 193-211.

Pornprom, T; Matsumoto, H; Usui, K; Ishizuka, K (1994) Characterization of oxyfluorfen tolerance in selected soybean line. *Pesticide Biochemistry and Physiology.* **50**, 107-114.

Reddy, K N; Nandihalli, U B; Lee, H J; Duke, M V; Duke, S O (1995) Predicting activity of protoporphyrinogen oxidase inhibitors by computer-aided molecular modeling. *American Chemical Society Symposium Series.* **589**, 221-224.

Reddy, K N; Dayan, F E; Duke, S O (1997) QSAR analysis of protoporphyrinogen oxidase inhibitors. In *Comparative QSAR* (ed. J. Devillers). Taylor and Francis, in press.

Scalla, R; Matringe, M (1994) Inhibitors of protoporphyrinogen oxidase as herbicides: diphenyl ethers and related photobleaching molecules. *Reviews in Weed Science.* **6**, 103-132.

Strierle, A; Upadhyay, R; Strobel G (1991) Cyperin, a phytotoxin produced by *Aschochyta cypericola*, a fungal pathogen of *Cyperus rotundus*. *Phytochemistry.* **30**, 2191-2192.

Theodoridis, G; Baum, J S; Hotzman, F W ; Manfredi, M C ; Maravetz, L L; Lyga, J W; Tymonko, J M; Wilson, K R; Poss, K M; Wyle, M J (1992) Synthesis and herbicidal properties of aryltriazolinones. A new class of pre- and postemergence herbicides. *American Chemical Society Symposium Series.* **504**, 135-146.

Usui, K; Pornprom, T; Matsumoto, H; Shirakura, S; Ishizuka, K (1995) Cross-tolerance of oxyfluorfen-tolerant soybean cells to protoporphyrinogen oxidase-inhibiting herbicides. *Weed Research.* **40**, 187-193.

Venkatasubbaiah, P; Van Dyke C G; Chilton W S (1992) Phytotoxic metabolites of *Phoma sorghina*, a new foliar pathogen of pokeweed. *Mycologia.* **84**, 715-723.

Ward, E R; Volrath, S (1995) Manipulation of protoporphyrinogen oxidase enzyme activity in eukaryotic organisms, International Patent Application No. WO 95/34659.

Weber, H A; Gloer, J B (1988) Interference competition among natural fungal competitors: An antifungal metabolite from the coprophilous fungus *Preussia fleischhakii*. *Journal of Natural Products.* **51**, 879-883.

JV 485 - AN ADVANCED PRE-EMERGENCE HERBICIDE FOR THE CONTROL OF ALOPECURUS MYOSUROIDES AND BROAD-LEAVED WEEDS IN UK WINTER WHEAT

B J G BOLTON, P W ROSE
Bayer plc, Crop Protection Business Group, Eastern Way, Bury St Edmunds, Suffolk IP32 7AH

A J NORTON
Monsanto plc, PO Box 53, Lane End Road, High Wycombe, Buckinghamshire HP12 4HL

ABSTRACT

JV 485 is a new herbicidal a.i. for use against grass and broad-leaved weeds in winter wheat. This paper summarises the results of more than 100 trials from 1995-1997. JV 485 shows strength against *Alopecurus myosuroides* and most broad-leaved weeds found in UK wheat including·*Galium aparine*. Following a pre-emergence application, surprising consistency and high levels of weed control were achieved, over a wide range of conditions. This reliability was superior to current pre- and post-emergence standards.

INTRODUCTION

JV 485 is a new herbicide discovered by Monsanto and jointly developed in Europe with Bayer. (Prosch *et al.*, 1997).

This paper reviews the results of three years trials carried out in the United Kingdom by Bayer and Monsanto. The main objective in these trials was to investigate activity against *Alopecurus myosuroides* and *Galium aparine*, but effects against other grass and broad-leaved weed species were also measured.

MATERIALS AND METHODS

JV 485 was tested as a 500 g/l SC formulation in all trials. The standards varied between seasons and trials protocols but the most commonly used were: pendimethalin 400 g/l SC; isoproturon (IPU) and diflufenican (DFF) as 500:50 g/l SC or 500:20 g/l SC; isoproturon in various formulations; clodinafop-propargyl and cloquintocet-mexyl 240:60 g/l EC; clodinafop-propargyl, cloquintocet-mexyl and trifluralin 12:3:383 g/l EC; an adjuvant mineral oil (970 g/l) was usually included where recommended with post-emergence treatments.

JV 485 was applied pre-emergence of the crop and weeds. It was compared with pre-emergence and post-emergence standards.

Trials were sited in commercial crops of winter wheat. Efficacy trials were sited in fields known to have an infestation of the target weed. Crop safety trials were generally carried out on weed-free sites.

Applications were made by knapsack plot sprayers pressurised by compressed gas. Nozzles were typically flat fan, selected to give a medium spray quality at an operating pressure of 2 - 3 bar and an application volume of 200 - 250 l/ha. Trials were of randomised block design with three or four replicates. Plot sizes were usually 10 - 18 m^2 in efficacy trials and in crop safety trials 36 - 45 m^2.

Crop density was assessed by counting samples of 5 x 1 m of row per plot. Weed control was normally assessed by counting surviving weeds, typically in 5 x 0.1 m^2 quadrats per plot or by estimates of % weed cover. In all trials where *A. myosuroides* was present a final quadrat count (5 x 0.1 m^2 quadrats/plot) of heads was made. Results for weed control have been included only from those trials which had an infestation level of at least five plants/m^2. Crop tolerance was assessed by whole plot scores of biomass and estimates of leaf area damaged. Grain yield from crop safety trials was measured by harvesting a strip through each plot with a combine-harvester. The weight of harvested grain was corrected to 14 % moisture content.

A. myosuroides seed samples from a number of trials in 1996 were tested at IACR Rothamsted for sensitivity to chlorotoluron and fenoxaprop-P-ethyl (Clarke *et al.*, 1994).

RESULTS

Crop tolerance - winter wheat

Pre-emergence treatments of JV 485 at the recommended rate of 175 g/ha were safe to a wide range of winter wheat cultivars. Slight necrotic spotting to the first emerging wheat leaves was observed in 27% of the trials. At the affected sites the mean leaf area damaged was only 2.8% at crop stages GS10-21, but this effect was transient and the crops grew away normally. Treatments applied at 350 g/ha were a little more damaging, but not permanently so. Crop density and grain yield assessments showed little or no effect from JV 485 (Table 1).

Table 1. Crop density (Mean of trials from three years, 1995-97) and grain yield (Mean of trials from two years, 1995-96), relative to untreated (= 100).

Pre-emergence treatments		Crop density			Relative yield		
	Rate a.i. g/ha	% rel.	Range	No. trials	% rel.	Range	No. trials
JV 485	175	99.7	91-114	46	100.1	93-109	11
JV 485	350	98.0	71-119	48	97.4	82-108	11
Pendimethalin	2000	96.2	65-116	39	98.7	87-104	11
Pendimethalin	4000	89.5	42-103	15	95.8	83-103	11

Crop tolerance - following crops

Trial sites were visited in the season following application of JV 485. Succeeding crops were established under normal farm practices and rotations. Grass (4 sites), linseed (1), maize (1), spring barley (1), spring beans (1), spring oilseed rape (4), set aside (4), sugar beet (3), triticale (1), winter barley (6), winter beans (9), winter oilseed rape (4), winter peas (1) and winter wheat (41) crops grown on land previously treated with JV 485 showed no detrimental effects.

Weed control - *A. myosuroides*

Efficacy trials on *A. myosuroides* were most frequently sited in crops grown on medium and heavy soils. These crops were established following a wide range of cultivation methods including minimum cultivations. Seedbed conditions varied greatly from a fine, level and moist tilth to very coarse, unconsolidated and dry soils. Trash from the previous crop was sometimes present, particularly under minimum cultivation systems. The results for *A. myosuroides* control (Table 2) showed JV 485 to be a consistently robust and reliable treatment. It compared very favourably with existing standard treatments, applied pre- or post-emergence, and a post-emergence sequence.

Table 2. *A. myosuroides* results from three seasons. (Mean % reduction in numbers of *A. myosuroides* heads).

Treatments	1995 trials			1996 trials			1997 trials		
	% red'n	Range	No.	% red'n	Range	No.	% red'n	Range	No.
Pre-emergence									
JV 485	89.7	69-100	23	90.7	71-100	32	94.3	80-100	23
Pendimethalin	80.2	59-98	13	71.3	0-99	25	74.0	0-97	11
IPU/DFF	66.4	11-94	10	-	-	-	-	-	-
Post-emergence									
IPU/DFF	83.0	21-100	23	74.3	3-100	27	72.8	22-99	18
Clodinafop/IPU/DFF	-	-	-	76.6	34-100	13	-	-	-
Clodinafop/trifluralin/oil	-	-	-	-	-	-	83.5	43-100	6
Clodinafop/oil (spring)	-	-	-	-	-	-	62.8	10-100	6
Post-emergence sequence									
IPU/DFF autumn followed by clodinafop/oil spring	-	-	-	-	-	-	95.7	85-100	7

Treatment doses

	g a.i./ha
JV 485	175
pendimethalin	2000
IPU/DFF	2500:100
clodinafop/IPU/DFF	30:1000:100
clodinafop	30
clodinafop/trifluralin	30:958

The field performance of JV 485 at those sites tested for resistance, at IACR Rothamsted, is shown in Table 3. Results from 1996 together with three trials from 1997 sited in tested fields, confirmed the reliability of *A. myosuroides* control by JV 485 compared with the standards. The reduced level of control from clodinafop/IPU/DFF at some sites appears to reflect the fenoxaprop resistance status. It must be acknowledged that for strict adherence to the recommendation an additive should have been included with clodinafop at this rate.

Table 3. Field performance of herbicides against *A. myosuroides* and resistance status of weed seed samples from individual sites.

	Field performance % red'n in heads				Resistance status*	
Trial number	JV 485	IPU/DFF	Clodinafop/ IPU/DFF	heads/m^2	Chloro-toluron Star rating	Fenox-aprop Star rating
Rate g a.i./ ha	175	2500:100	30:1000:100			
Timing	pre-em.	post-em.	post-em.			
95-164-086/093	94	96	-	14	5	5
WR-05-96	92	44	-	266	5	5
96-164-034	96	40	92**	197	5	5
95-274-032	93	95	-	34	3	5
95-274-034/036	84	53	-	1227	3	5
NM-03/05-96	81	63	93	249	3	2
MR-03/06-96	90	78	36	45	2	5
SR-06/08/13-96	91	50	41	2033	2	5
MR-04/07-96	95	3	34	25	1	5
WR-03/06-96	95	13	67	556	1	5
95-274-033	71	60	-	26	1	2
NR-02-96	81	91	98	918	1	2
SW-08-96	97	-	-	127	1	1
ER-07/14/15-96	98	100	99	761	1	S
NR-05/09/13-96	100	-	-	593	S	3
SW-05-96	95	97	93	240	S	3
NR-04-97	93	87	100**	1116	S	3
NM-04/17-96	80	67	95	157	S	2
SR-07/09/16-96	90	97	100	1000	S	2
Mean	90.3	66.7	79.0			

* 5 = highest level, 1 = lowest level, S = Susceptible.

** clodinafop/trifluralin 30:958 g/ha with oil

Table 4. Efficacy against *Galium aparine* (mean of years 1995-97)

	Rate a.i.g/ha	*Galium aparine* % red'n. in nos./biomass Mean	Range	%. trials >95% red'n.	Total no. trials
Pre-emergence treatments					
JV 485	125	88.7	3-100	63	27
JV 485	150	91.7	47-100	75	12
JV 485	175	96.1	62-100	81	26
Pendimethalin	2000	65.1	0-100	18	11
Post-emergence treatment					
IPU/DFF	2500:100	71.7	0-100	16	19

Weed control - *Galium aparine*

Control of *Galium aparine* with JV 485 was excellent at 175 g/ha, but efficacy and reliability, as shown by the range, declined at lower rates (Table 4).

Weed control - other weeds (Table 5)

JV 485 gave good control of autumn germinating *Avena fatua* but its overall effect against this weed was less reliable than the standard, due to variable activity against spring germinating weeds.

JV 485 has consistently shown excellent control of *Poa annua* and *Lolium multiflorum.* Reliable reduction of *Bromus sterilis* has been shown and results from a single trial indicate that use in sequence with other herbicides can result in good control of this species.

Table 5. % reduction in numbers/biomass of other weed species (where two or more results were obtained) with JV 485.

Rate a.i. g/ha	JV 485 pre-emergence 175	No. of trials	IPU/DFF post-emergence 2500:100	No. of trials
Grass weeds				
Avena fatua	82	10	93	10
Bromus sterilis	82	7	44	6
Lolium multiflorum	97	3	91	2
Poa annua	99	7	100	5
Broad-leaved weeds				
Aethusa cynapium	91	2	26	1
Aphanes arvensis	94	2	80	2
Brassica napus	99	18	69	16
Capsella bursa-pastoris	100	3	100	3
Geranium spp.	100	3	95	3
Lamium purpureum	100	3	100	2
Matricaria spp.	100	9	100	7
Myosotis arvensis	99	8	100	7
Papaver rhoeas	99	6	83	6
Sinapis arvensis	94	8	94	7
Stellaria media	98	25	97	23
Veronica hederifolia	78	14	86	14
Veronica persica	100	21	79	20
Vicia faba	77	4	90	3
Viola arvensis	100	5	99	5

DISCUSSION

Efficacy with JV 485 against *A. myosuroides* was more reliable than the widely used commercial standards. Control was consistent in trials over three seasons, showing reliability despite variations in soil and weather conditions. The activity of pre-emergence herbicides is inevitably influenced by seedbed condition, moisture and soil texture. What is particularly encouraging from the data presented here is the remarkable reliability of JV 485 from usage over a wide range of practical conditions. Control remained good despite some very poor seedbed conditions. This was presumably a feature of shoot uptake of JV 485 (Prosch *et al.*, 1997), making efficacy less dependent on soil and moisture conditions than for herbicides relying on root uptake.

JV 485 offers a new approach to the increasingly difficult problem of controlling *A. myosuroides*. A reliable treatment applied soon after drilling and effective in a wide range of soil conditions, JV 485 will give farmers early control of *A. myosuroides*. In difficult situations where growers may need to use sequences of herbicides, JV 485 offers early weed control, allowing better timing of any subsequent treatment which might be necessary.

It is clearly desirable that any new chemical should be effective against weed populations resistant to existing herbicides. This would seem to be the case with JV 485. Its clear activity in glasshouse and pot experiments (Moss & Rooke, 1997) against *A. myosuroides* populations showing resistance to other herbicides was supported by field results (Table 3).

JV 485 has shown good activity against a range of other grass weeds. The activity against *B. sterilis* is useful. JV 485 could be the initial treatment in a sequence of herbicides giving good control of this weed.

Another major benefit demonstrated by JV 485 was the effective control of *G. aparine*, which has proved difficult to control with autumn-applied residual herbicides. Control of other broad-leaved weeds was equivalent to the widely used and effective standard, isoproturon and diflufenican (Table 5).

JV 485 is a significant new herbicide with a unique combination of efficacy, reliability and wide spectrum activity which will be of great benefit to U.K. wheat growers, particularly those faced with the increasingly difficult problems of controlling *A. myosuroides* and *G. aparine*.

ACKNOWLEDGEMENTS

Thanks are due to all those involved in the field trials work, including the farmers who co-operated; also to Dr Moss and colleagues at IACR Rothamsted for the resistance testing.

REFERENCES

Clarke J M; Blair A M; Moss S R (1994). The testing and classification of herbicide resistant *Alopecurus myosuroides* (black-grass). *Aspects of Applied Biology,* **37,** *Sampling to Make Decisions,* 181-188.

Moss, S R; Rooke, M S (1997). Activity of JV 485 a protoporphyrinogen oxidase inhibitor, on herbicide resistant blackgrass *(Alopecurus myosuroides)*. *Proceedings British Crop Protection Conference - Weeds.*

Prosch, S D; Ciha, A J; Grogna, R; Hamper, B C; Feucht, D and Driest, M; (1997). JV 485, a new herbicide for pre-emergence broad spectrum weed control in winter wheat. *Proceedings British Crop Protection Conference - Weeds.*

RICE ALLELOPATHY - WHERE ARE WE AND HOW FAR CAN WE GET?

M OLOFSDOTTER*, D NAVAREZ, M REBULANAN
International Rice Research Institute, Agronomy, Plant Physiology and Agroecology Division, PO Box 933, 1099 Manila, Philippines

ABSTRACT

Widespread and increasing environmental concerns on herbicide use have worked as an eye-opener for alternative and new approaches for weed control. One of the new approaches is the attempt to utilize allelopathic potential in crops for weed suppression in the field. Allelopathy is the direct influence from one living plant on growth and development of another plant (Olofsdotter *et al.*, 1995). As such, allelopathy research in rice has made remarkable progress in the last decade opening up for new possible strategies for weed control in rice.

Allelopathic potential in growing rice was first found in a seed increase plot at Arkansas Rice Research Institute (Dilday *et al.*,1991). Since then, several groups all over the world have been working on screening rice cultivars for allelopathic potential, evaluated the possibilities for utilizing allelopathic features in rice for weed control, tried to find the allelochemicals responsible for allelopathic potential in rice, evaluated trade off effects from allelopathic potential in rice, and evaluated the possibilities for genetic improvements of rice cultivars to increase plant interference potential both from allelopathy and competition etc..

Weed science needs a paradigm shift where naturally occurring defense mechanisms against weeds are viewed as a possible strategy for weed management. With this paradigm shift we could create a breeding strategy for the future where cultivars are made "resistant" to one or several special weed problems.

INTRODUCTION

In the last decade an intensive research effort has been put into finding new or redesigned weed control methods to reduce herbicide dependency all over the world. Most research activities have been in managerial weed control measures, in biological control and within mechanical weed control, but also genetic improvement for increased competitive ability of the crops has recently reentered the research agenda. Competitive ability is often viewed as the whole plant interference complex which should, more correctly, be distinguished into competition and allelopathy, where competition is the unequal sharing of resources and allelopathy the addition of chemicals to the environment. In doing so, it is possible to combine and optimize both in a final weed suppressing cultivar.

---

* Mailing address: Weed Science, Thorvaldsens vej 40, DK-1871 Frederiksberg C, Denmark

Rice is the most important food cereal, worldwide creating the daily basic source of nutrient for billions of people. Herbicide use in rice production is increasing dramatically, and traditional weed management strategies for rice are no longer applied in many places. Labor for hand weeding is becoming too expensive, and lack of timely and suitable irrigation water reduces the managerial weed control possibilities. It is therefore of the greatest interest and necessity to develop new strategies for weed management in rice to ensure sustainable rice supply to the growing population.

Along with other alternative weed management strategies, research on rice allelopathy was started almost a decade ago. The discovery of some rice cultivar capable of suppressing germination and growth of ducksalad (*Heteranthea limosa*) under field conditions, with something more likely to be a chemical reaction than competition, was the starting point for rice allelopathy research (Dilday *et al.*, 1991). Since then, researchers all over the world have been trying to understand allelopathy in rice. This paper will review the work on rice allelopathy so far and try to put up some modest proposals of research directions for the future.

WHERE ARE WE ON RICE ALLELOPATHY?

Allelopathy in rice was first discovered in non-replicated seed increase plots with a natural infestation of ducksalad *(Hetherantera limosa)* at Arkansas Rice Research Institute. Over two seasons, 10,000 rice accessions were evaluated for allelopathic potential against ducksalad. Of these, 3.5% were categorized as allelopathic as they had a weed free radius at the base of the rice plant > 10 cm (Dilday *et al.*, 1991). This discovery was the start for rice allelopathy research in many places of the world. In Arkansas today, 12,000 accessions have been evaluated for allelopathic potential against ducksalad and 5,000 accessions against redstem (*Purple ammannia).* The results showed that 412 rice accessions were allelopathic against ducksalad with a weed free radius >10 cm and 145 against redstem. Sixteen rice accessions were allelopathic to both ducksalad and redstem (Dilday *et al.*, 1997). The rice accessions with allelopathic potential originated from 37 countries indicating that allelopathy is widespread in rice germplasm. 1,000 rice accessions have been screened for allelopathic potential against *Echinochloa crus-galli* and *Cyperus difformis* in field experiments in Egypt. Of these 30 accessions showed promising allelopathic potential (50-90% weed reduction) against *E. crus-galli* and 15 were allelopathic (30-75% weed reduction) against *C. difformis*. Five cultivars showed strong allelopathic potential for both weed species (Hassan *et al.*, 1997). The selectivity in weed control from rice cultivars, shown both in Arkansas and Egypt, indicate that several chemical compounds with selective action against weeds are involved in allelopathy.

Even though the results from Egypt and Arkansas seem reliable and promising, there is a problem in conducting allelopathy experiments in the field only, as competition and allelopathy cannot be distinctly separated in the field. Field studies must, therefore, be combined with laboratory experiments where competition can be eliminated as a cause of observed interference (Olofsdotter & Navarez 1995). Also, for the sake of breeding for allelopathic potential, where the number of seeds is limited, a simple screening procedure is desirable. At IRRI (International Rice Research Institute) a laboratory screening procedure for allelopathic potential in rice has been established (Navarez & Olofsdotter, 1996). Seeds of *E. crus-galli* are relay-seeded into a petri dish with 7-day-old rice seedlings. The plants are grown together for 10 days before measuring the root length of *E. crus-galli*. Allelopathic rice causes severe root growth inhibition and, in strongly allelopathic cultivars, pruning of the root tip of the weed. This screening procedure has been used to ensure that observations from the field were allelopathy and not competition (Olofsdotter & Navarez, 1996). The screening in combination with field experiments have consistently shown that 19 rice cultivars out of 111 tested were able to suppress the growth of *Echinochloa crus-galli* by > 40%, measured as weed dry weight 8 weeks after seeding (WAS) in three seasons in 1995 and 1996. Seven of these cultivars reduced *E. crus-galli* dry weight by > 50% in all three growing seasons (Olofsdotter *et al.*, 1997). Two field experiments with *Trianthema portulacastrum* as the target weed and with the same 111 rice cultivars showed 2 rice cultivars that were strongly allelopathic to both *E. crus-galli* and *T. portulacastrum*. This verifies the pattern from Arkansas and Egypt, indicating more than one chemical to be responsible for the allelopathic effect. One of the rice cultivars (Taichung native 1) has shown allelopathic effect against *E. crus-galli*, *T. portulacastrum*, *H. limosa* and *P. ammannia* (Dilday *et al.*, 1997; Olofsdotter & Navarez, 1996). This cultivar is also carrying the gene for semi-dwarfism which is present in all modern varieties of rice. The genetic relationship could be the reason why many modern rice varieties have allelopathic potential. Some of the cultivars giving promising results at IRRI have also been tested under field conditions in Korea with results comparable to those obtained in the Philippines (Kim & Shin, 1997). This is promising, from a breeding point of view, as it is very important that a character is stable over several seasons and environments.

Knowing which chemicals that are causing the allelopathic effect is another factor that would make breeding for allelopathy easier. So far no breakthroughs have been achieved in trying to characterize chemicals involved in rice allelopathy. However, recent work has shown significantly higher levels of 3-hydroxybenzoic acid (3HBA), 4-hydroxybenzoic acid (4HBA), 4-hydroxyhydrocinnamic acid (4HHCA), 3,4-dihydroxyhydrocinnamic acid (34DHHCA) and tentatively identified 4-hydroxyphenylacetic acid (4HPAA) in water from allelopathic rice cultivars when compared with water from the non-allelopathic cultivar Rexmund (Mattice *et al.*, 1997). All these chemicals are phenolic acids which have been described as allelochemicals in many plant species. However, the very selective mode of action seen in field testing of allelopathic cultivars, points in the direction that allelochemicals in rice should be specific and not so common as phenolic acids. One reason why phenolics are released in higher concentrations from allelopathic cultivars could be a higher activity of the general defense mechanisms of these plants. At IRRI, work on phosphate efficiency in upland rice under severe phosphate deficiency have shown positive correlation between cultivars capable of releasing phosphorus from the soil and the allelopathic cultivars (Findenegg & Kirk, 1997). The search for allelochemicals in rice should therefore continue and other groups of chemicals should also be investigated before a conclusion is drawn on allelochemicals in rice.

HOW FAR CAN WE GET?

Rice accessions with allelopathic activity have different origin and are at different stages of improvement. This means that allelopathic potential is widespread and already unconsciously included in several breeding programs. However, to reach the goal of weed fighting rice cultivars a conscious selection for allelopathy and competition must be done.

Knowledge about the genetic nature of allelopathy would be helpful in designing a breeding strategy for allelopathy. Preliminary genetic studies indicate that allelopathy in rice is a quantitatively inherited feature. Also, experience with environmental impact on the strength and expression of allelopathy, such as seasonal variation, weed density, soil type and crop density, support the hypothesis of quantitative inheritance (Dilday *et al.*, 1997; Courtois & Olofsdotter 1997). As such, it has to be included in the breeding process at an early stage and cannot be genetically modified in varieties which are already high yielding. For us, as weed scientists, this means that we should work together with the breeders by supplying information on allelopathic potential, and help in the selection of parental material to be used in the breeding program. Subsequently, we probably have to wait for a number of seasons before the breeding material is put under weed pressure, as very few breeders would accept the presence of weeds in their fields. This strategy has been used in Arkansas, where they have achieved a high yielding cultivar (out-yielding any of the parents) with strong allelopathic potential against *H. limosa* (Dilday *et al.*, 1997). However, a broader spectrum of target weeds would be desirable and continued connection between weed scientists and plant breeders could enable the creation of high yielding cultivars that are strongly allelopathic against several common weed species.

With allelopathic potential widely spread in the germplasm there are also opportunities to breed locally adapted allelopathic cultivars, bred for taste and environment in a given geographical area. This could be done with "farmer participatory breeding", still with breeders and weed scientists working together.

The limit for success in introducing allelopathic potential into rice cultivars is probably more psychological than realistic. Weed science needs a paradigm shift, where naturally occurring defense mechanisms against weeds are viewed as a possible strategy for weed management. With this paradigm shift we could learn from plant pathologists and create a breeding strategy for the future, where cultivars are made "resistant" to one or several specific weed problems.

RESEARCH TO REACH THE GOAL

Even though the possibilities seem to be present for a scientific breakthrough in use of allelopathy for weed management, there are still many problems to be solved and questions to be asked. First of all we need to screen more rice cultivars for allelopathic potential and to be able to select for allelopathic potential at an earlier stage in the breeding program and, we need to improve the screening techniques to enable laboratory screening when seeds are limited.

Secondly, we need to know which chemicals are causing the allelopathic effects. Many secondary metabolites in plants have phytotoxic effects, and such chemicals can be found in almost all plant species (Putnam, 1986). However, for these chemicals to become allelochemicals, effective against weeds, they need to be released from a living plant. It is therefore important that efforts to identify allelochemicals are done on chemicals actually released from the plant. After knowing what the allelochemicals are, we can start clarifying the production and release of these chemicals and how this interacts with different growing environments. This is important to enable manipulations to get a greater expression of allelopathic potential in the field. Further work on allelochemicals should also include studies of principles of selectivity among weeds and synergistic effects among allelochemicals.

Another question that needs to be addressed is the physiological cost of allelopathy. Production of allelochemicals might be an energy costly affair for the plants, using resources that otherwise could be used for kernel production. So far, no results point in the direction of a high yield penalty caused by allelopathy, but experiments needs to be designed and conducted to prove this. Actually, the high frequency of allelopathic potential in the breeding material suggests weak negative correlation with traits already included in the selection process such as yield and disease resistance. However, the physiological costs, small or large, may determine the target ecosystems where allelopathic rice will be suitable.

Deliberate release of phytotoxic chemicals, such as allelochemicals released from plants, will always occur in the environment for a longer or a shorter time. Natural products, such as allelochemicals must be biodegradable, otherwise we would be able to see widespread consequences caused by allelopathic plants. During degradation of allelochemicals sub-lethal doses will occur, and these doses will put a selection pressure on the weed population. In herbicide science such sub-lethal doses are said to affect the development of herbicide resistant weed species. It is therefore of great importance that allelochemicals are studied with the aim to foresee a possible development of resistance. If allelochemicals act synergistically with different modes of action it is not likely that allelopathic cultivars would create a resistance problem, but we still need to confirm this theory.

The ecotoxicological consequences of deliberate release of allelochemicals should also be studied carefully. In a situation where allelopathic cultivars could be grown on large areas releases of allelochemicals could become an environmental problem. Even though concentrations outside the rice field are believed to be low, such concentrations could create changes in the fauna and flora in non-target environments. As most rice is grown under irrigated conditions, and contamination of water in rice growing areas is very likely, it is also important to study allelochemical effects on non-target organisms, such as fish, bird etc...

Finally, plant interference as the result of the combined effect of allelopathy and competition should be seen as a component of integrated weed management (IWM). It is also important to relate allelopathic rice with a shift in herbicide use from pre-emergence to post-emergence applications which would give us the opportunity of spraying if necessary and not as an precaution.

As seen there are still many questions, but allelopathy in rice, if given suitable attention in the coming year, could be used as a model system for utilization of allelopathy for weed control in other crops.

ACKNOWLEDGMENT

The author wants to thank DANIDA for providing the financial support for this research.

REFERENCES

Courtois B; Olofsdotter M. (1997) Breeding upland rice for allelopathic potential. In *Allelopathy in rice* (M. Olofsdotter ed.) International Rice Research Institute, In Press.

Dilday RH, Nastasi P, Lin J, Smith RJ Jr. (1991) Allelopathic activity in rice (*Oryza sativa* L.) against ducksalad (*Heteranthea limosa* (sw.) Wild.). *Sustainable agriculture for the Great Plains, Symposium proceedings*; USDA 255p, p 193-201.

Dilday RH, Yan WG, Moldenhauer KAK, Gravois KA., (1997) Allelopathic activity in rice (*Oryza sativa* L.) to major aquatic weeds. In *Allelopathy in rice* (M. Olofsdotter ed.) International Rice Research Institute, In Press.

Findenegg GR, Kirk GJD, (1997) Stimulated exudation of D-gluconic, shikimic and citric acids by roots of phosphate-starved rice cultivars. *Journal of experimental agriculture*. In press

Hassan SM. Aidy IR. Bastawisi AO. Draz AE. (1997) Weed management in rice using allelopathic rice varieties in Egypt. In *Allelopathy in rice* (M. Olofsdotter ed.) International Rice Research Institute, In Press.

Kim KU, Shin DH, (1997) Rice allelopathy research in Korea. In *Allelopathy in rice* (M. Olofsdotter ed.) International Rice Research Institute, In Press.

Navarez D, Olofsdotter M, (1996) Relay seeding technique for screening allelopathic rice *(Oryza sativa). Proceedings of the Second International Weed Control Congress.* 25-28 June 1996, Copenhagen, Denmark. Vol IV:1285-1290.

Mattice J, Lavy T, Skulman B, Dilday RH, (1997) A search for the allelochemicals in rice responsible for the control of ducksalad. In *Allelopathy in rice* (M. Olofsdotter ed.) International Rice Research Institute, In Press.

Olofsdotter M, Navarez D, (1995) Approaches in rice allelopathy research. *Proceedings of the 15th Conference of the Asian-Pacific Weed Science Society*. Vol 1A:315-321.

Olofsdotter M, Navarez D, (1996) Allelopathic rice for *Echinochloa crus-galli* control. *Proceedings of the Second International Weed Control Congress*. 25-28 June 1996, Copenhagen, Denmark. Vol IV:1175-1181

Olofsdotter M, Navarez D, Streibig JC, (1997) Weed suppressing rice - allelopathy for *Echinochloa crus-galli* control. *Weed Research.* In prep.

Putnam AR, 1986. Allelopathy: can it be managed to benefit horticulture? *HortScience* 21:411-413

THE CRITICAL PERIOD OF WEED COMPETITION AND ITS APPLICATION IN ORGANIC WINTER WHEAT

J P WELSH, H A J BULSON, C E STOPES
Elm Farm Research Centre, Hamstead Marshall, Near Newbury, Berkshire RG20 OHR, UK

A J MURDOCH
Department of Agriculture, The University of Reading, Earley Gate, PO Box 236, Reading RG6 6AT, UK

R J FROUD-WILLIAMS
Department of Agricultural Botany, The University of Reading, Earley Gate, Reading RG6 6AU, UK

ABSTRACT

Two experiments were conducted in central southern England between September 1994 and August 1996 to identify the critical weed free period in organically grown winter wheat. In competition with a mixed weed infestation of predominately *Alopecurus myosuroides* and *Tripleurospermum inodorum* it was found that wheat yield decreased as the duration of the weed infested period increased and that the crop needed to be kept weed free from sowing in order to completely avoid yield loss. Also, weeds emerging in the wheat crop (predominately *T. inodorum*) during the growing season had a significant and detrimental effect on yield and there was no point when weeding could be relaxed to avoid a yield penalty. Therefore, the existence of the critical period depends on the imposition of an acceptable yield loss. If a 10% yield loss gives a marginal benefit compared with the cost of weed control, the critical period will begin at 645 °Cdays after sowing (November) and end at 1223 °Cdays after sowing (March). This information could be used by farmers to target mechanical weed control operations to control weeds at a time which will have maximum benefit to the crop.

INTRODUCTION

Weeds have been identified as the major agronomic problem associated with arable crop production in organic farming systems (ADAS, 1992). Mechanical weed control in cereal crops can be broadly split into two methods; spring-tine weeding and inter-row hoeing (Rasmussen & Ascard, 1995). Spring-tine weeding is by far the most common method of mechanical weed control in organic cereal crops, whilst inter-row hoeing is relatively uncommon in the UK. However, at present, there is little information on the optimum timing of mechanical weed control and its ability to control weeds and produce a crop yield benefit (Rasmussen, 1996).

To identify the optimum timing for weeding operations, it seems appropriate to identify the period when weeds are likely to exert their greatest competitive effect on the crop viz. the critical period of weed competition. Once this period has been identified, it will be possible to target mechanical weeding operations appropriately.

The critical period represents the time interval between two separately measured components: the maximum weed-infested period or the length of time that weeds which have emerged with the crop can remain before they begin to interfere with crop growth; and the minimum weed free period or the length of time a crop must be free of weeds after planting in order to prevent yield loss (Weaver *et al.*, 1992). These components are experimentally determined by measuring crop yield loss as a function of successive times of weed removal or weed emergence, respectively. Currently, there have been no studies investigating the critical period in winter wheat.

Therefore, the aim of this work was to identify the critical weed free period in organically grown winter wheat and consider the potential use of this information for targeting the effective use of mechanical weeding techniques.

MATERIALS AND METHODS

Two experiments were conducted between September 1994 and August 1996 in organic winter wheat (cv. Mercia) at Elm Farm Research Centre, Berkshire. The altitude was 60m, rainfall 710 mm/year and the soil was a Wickham series clay loam grade 3-4. Wheat was drilled at a seed rate of 220 kg ha^{-1}. The experiments relied on the indigenous weed flora to provide competition against the crop.

The experimental design each year was a randomised block design with three blocks. Each block consisted of 16 plots. The plot size was 1.5m x 1.5m which included a 0.25m discard around a 1m x 1m sampling area. Eight of the plots were kept weed free from sowing for different durations including a weed free control, whilst the remaining eight plots had weeds present from sowing for different intervals including an unweeded control. The timing of treatments was altered in the 1995/96 season compared with the previous season to concentrate on the spring where it was considered the critical period was most likely to occur. The dates and crop growth stages (Zadoks *et al.*,1974) when weeding started or finished are given in Table 1.

The weeds were removed by hand to avoid damage to the crop and to minimise soil disturbance. Trampling effects were prevented by using raised scaffolding planks to access individual plots. Weed density was assessed in October/November using one 0.25 m^2 quadrat per plot. Weed dry matter was assessed from the plots that were being weeded for the first time using one 0.25 m^2 quadrat per plot. The crop was harvested by hand from the central one m^2 of each plot and the ears counted and then threshed using a Wintersteiger thresher to determine crop grain yield.

The data was subjected to regression analysis using GENSTAT 5.3 and statistical significance was taken at the $P \leq 0.05$ level. Block II of the experiment conducted in 1994/95 was omitted from the statistical analysis due to a severe edge effect, whilst block I was omitted from the 1995/96 experiment due to a very low weed population.

Table 1. Timing, crop growth stage (GS) and TSum of weeding treatments in 1994/95 and 1995/96

1994/95			1995/96		
Timing	Crop GS	Tsum (°Cd)	Timing	Crop GS	Tsum (°Cd)
30-Sep-94	Sown	0	28-Sep-95	Sown	0
11-Nov-94	13	413	30-Nov-95	22	693
05-Dec-94	22	671	25-Feb-96	23	1045
10-Jan-95	22	797	11-Mar-96	24	1109
06-Feb-95	22	930	28-Mar-96	24	1179
06-Mar-95	22	1097	17-Apr-96	26	1332
10-Apr-95	25	1353	10-May-96	33	1553
09-May-95	31	1650	30-May-96	34	1754
01-Aug-95	Harvest	2941	16-Aug-96	Harvest	3012

RESULTS

Weed density & dry matter production

In 1994/95 the weed flora in October comprised: *Tripleurospermum inodorum* (290 plants m^{-2}), *Aphanes arvensis* (92 plants m^{-2}), *Stellaria media* (36 plants m^{-2}) and *Agrostis gigantea* (16 shoots m^{-2}). In 1995/96 weed infestations were considerably greater than in the previous season: *Alopecurus myosuroides* (348 plants m^{-2}), *T. inodorum* (272 plants m^{-2}), *S. media* (24 plants m^{-2}) and *A. arvensis* (8 seedlings m^{-2}). The total weed dry matter when assessed in May was 16.38 g m^{-2} in 1994/95 and 604.78 g m^{-2} in 1995/96.

Crop grain yield

The grain yield of the weed-free control was 5.36 t ha^{-1} (unweeded control = 4.32 t ha^{-1}) in 1994/95 and 5.97 t ha^{-1} (unweeded control = 3.21 t ha^{-1}) in 1995/96.

There was no statistically significant relationship between crop yield and the duration of either the weed infested (F pr.=0.488, s.e. observations = 1.17) or weed free periods (F pr. = 0.551, s.e. observations = 1.02) in 1994/95 (data not presented). In the following season, however, the relationship between crop grain yield and the duration of both the weed infested period and the weed free period was statistically significant and was most accurately described by a logistic function:

$$Y = a + \frac{c}{1 + e^{(-b(t-m))}} \qquad (1)$$

where *Y* is the grain yield as a percentage of the weed free control, *t* is thermal time (base temperature = 0 °C) from sowing (Tsum; °Cday) and *a,b,c* and *m* are constants. It was necessary to set the y-intercept of the curve at the level of the weed free control in the case of weed infested periods and at the level of the unweeded control in the case of the weed-free periods. This was achieved by fixing the values of the *a* and *c* constants (Table 2) in the logistic function (Equation 1).

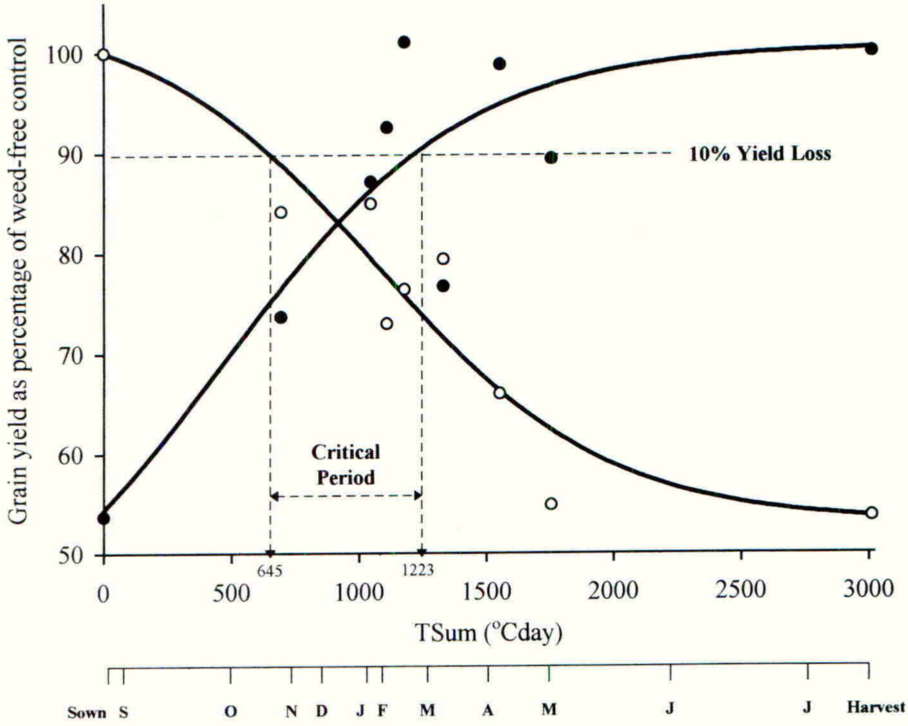


Figure 1. Observed and fitted wheat grain yield (% of weed free control) as affected by the duration of the weed infested period (○, ———) and weed free period (●, ———) in 1995/96. Parameter estimates are given in Table 2.

Crop yield decreased as the duration of the weed infested period increased (Figure 1). The model demonstrated that competition between the crop and weed population (principally *A. myosuroides* and *T. inodorum*) occurred throughout the season, although, the rate of yield reduction was greatest between 500 and 1500 °Cdays after sowing. Crop yield also increased as the duration of the weed free period increased (Figure 1). However, it is important to note that there was no further emergence of *A. myosuroides* after the initial flush at sowing and, therefore, after the first weeding treatment the crop was competing with principally *T. inodorum* during the growing season.

Table 2. Parameter estimates, standard errors (s.e.), % variance accounted for (% va) and F probability (F*P*) of fitted lines for wheat yield as a function of weed infested and weed free periods in 1995/96.

	Constants							
Parameter	*a*	*c*	*b*	s.e.	*m*	s.e.	% va	F*P*
Weed infested period	53.00	51.40	-0.002205	0.000489	1073.6	72.6	80.7	<0.001
Weed free period	36.50	64.18	0.002097	0.000446	454.0	126.0	69.4	<0.001

DISCUSSION

The low weed infestation in the 1994/95 experiment would have been unlikely to have had a significant competitive effect on the crop and, therefore, it is not surprising that the presence of a critical period could not be found.

In 1995/96 there was a considerably greater level of weed present, both in terms of density and dry matter production. The logistic model (Equation 1) fitted to the weed infested data suggests that competition occurred continuously throughout the season. This is in close agreement with the work reported by Wilson *et al.* (1985) and Read & Hewson (1988) who both found that competition from *A. myosuroides* started early in the growing season. However, Moss (1987) observed that the effects of *A. myosuroides* on crop growth prior to April were relatively small, but increased rapidly between April and June. In North America, Rydrych (1974) demonstrated that winter wheat could tolerate competition from *Bromus tectorum* until March without suffering a yield reduction, but after this time crop yield declined sharply. A possible explanation for the difference in results between this present study and the work conducted by Moss (1987) and Rydrych (1974) may be the competitive pressure of the weed population. In this study the crop was competing with a total weed density of 652 plants m^{-2} whilst the experiments conducted by Moss (1987) had 500 plants m^{-2} and Rydrych (1974) 130 plants m^{-2}, therefore, it may be assumed that the crop was facing a greater level of competition. This view is supported by Niemann (1979) who reported that the onset of competition depended on weed density and started earlier in the growing period the greater the density.

The model fitted to the weed free periods demonstrated that weeds emerging in the crop during the growing season were also having a significant and detrimental effect on crop yield. It suggested that there was no point in the growing season when weeding operations could be ended if crop yield loss was to be completely avoided. This is surprising since spring emerging weeds would not have been considered to pose a strong competitive effect on a vigorous autumn sown crop (Wilson, 1980).

According to the definition of the critical period by Weaver *et al.* (1992), the experiment in 1995/96 showed there to be no critical period in an organically grown winter wheat crop. However, there is likely to be a point when the effort, cost and difficulty of weeding outweighs the yield benefit. Therefore, a decision needs to be taken on the level of an acceptable yield loss before the critical weed free period can be identified. The calculation of an acceptable yield loss will depend on the costs of weeding in relation to the yield benefit achieved. For example, if a 10% yield loss gives a marginal benefit compared with the cost of weed control, the critical period will begin at 645 °Cdays after sowing (early November) and end at 1223 °Cdays after sowing (late March) (Figure 1). Clearly, the greater the yield loss the farmer is prepared to accept, the shorter the critical weed free period will become.

The practical application of this information is dependent on the method of weed control used. For example, Welsh *et al.* (1996) reported that spring-tine weeding controlled *Papaver rhoeas* most effectively in the autumn, whilst spring treatments resulted in considerably poorer levels of control. Therefore, if *P. rhoeas* is at a competitive density, it will need to be controlled at an early stage in the growing season to ensure that it is removed before the onset of the critical period. This is contrary to current farmer practise in the U.K. with this type of weeder which tends to focus on spring weeding treatments. However, Welsh *et al.* (In Press) demonstrated that inter-row hoeing in winter wheat could effectively control weeds at a wide range of timings, regardless of weed growth stage and, therefore, would be able to control weeds just prior to or during the critical period. Therefore, a combined strategy of spring-tine weeding in the autumn followed by inter-row hoeing, if necessary, in the early spring should allow the farmer to minimise the impact of weeds during the critical period.

The concept of the critical weed free period can, therefore, be used to target the timing of mechanical weeding operations to ensure maximum benefit to the crop. In the case of inter-row hoeing, weeding can take place effectively just prior to or during the critical period, whilst spring-tine weeding will need to be carried out prior to the critical period, when weeds are smaller and consequently more vulnerable to control.

ACKNOWLEDGEMENTS

The authors wish to thank the European Union for their funding (AIR3-CT93-0852). We would also like to thank Dr. John Cussans & Dr. Peter Lutman of IACR Rothamsted for their help with the statistical analysis and Lawrence Woodward for his advice and comments throughout this project. Finally, we would like to thank all of the staff at EFRC.

REFERENCES

ADAS (1992) ADAS Organic Wheat Survey. *New Farmer & Grower.* **34**, 31-33.

Moss, S R (1987) Competition between black-grass (*Alopecurus myosuroides*) and winter wheat. *Proceedings 1987 British Crop Protection Conference - Weeds,* Brighton, 367-374.

Niemann, P (1979) Einfluss unterschiedlicher dauer der unkrautkonkurrenz auf die ertragbestimmenden faktoren der wintergerste. *Proceedings European Weed Research Society Symposium: The influence of different factors on the development and control of weeds*, 161-171.

Rasmussen, J; Ascard, J (1995) Weed control in organic farming systems. In: *Ecology and Integrated Farming Systems* (eds.) D M Glen, M P Greaves and H M Anderson. John Wiley & Sons Ltd., England. 49-68.

Rasmussen, J (1996) Mechanical weed management. *Proceedings of the 1996 Second International Weed Control Congress,* Copenhagen, 943-948.

Read, M A; Hewson, R T (1988) Control of *Alopecurus myosuroides* (black-grass) in winter cereals with isoproturon - a summary of trials carried out over sixteen years in the UK. *Aspects of Applied Biology.* **18** - *Weed control in cereals and the impact of legislation on pesticide application,* 157-162.

Rydrych, D J (1974) Competition between winter wheat and downy brome. *Weed Science.* **22**, 211-214.

Weaver, S E; Kropff, S E; Groeneveld, R M W (1992) Use of ecophysiological models for crop-weed interference: The critical period of weed interference. *Weed Science.* **40**, 302-307.

Welsh, J P; Bulson, H A J; Stopes, C E; Froud-Williams, R J; Murdoch, A J (1996) Weed control in organic winter wheat using a spring-tine weeder. *Proceedings of the 1996 Second International Weed Control Congress,* Copenhagen, 1127-1132.

Welsh, J P; Bulson, H A J; Stopes, C E; Froud-Williams, R J; Murdoch, A J (In Press) Mechanical weed control in organic winter wheat. *Aspects of Applied Biology* **50**, - *Optimising cereal inputs-its scientific basis.*

Wilson, B J (1980) The effect on yield of mixtures and sequences of herbicides for the control of *Alopecurus myosuroides* Huds. and broad-leaved weeds in winter cereals. *Weed Research.* **20**, 65-70.

Wilson, B J; Thornton, M E; Lutman, P J W (1985) Yields of winter cereals in relation to the timing of control of black-grass (*Alopecurus myosuroides* Huds.) and broad-leaved weeds. *Aspects of Applied Biology.* **9**, -*The biology and control of weeds in cereals*, 41-48.

Zadoks, J C; Chang, T T; Konzak, C F (1974) A decimal code for the growth stages of cereals. *Weed Research.* **14**, 415-421.

THE IMPLICATIONS OF REDUCED DOSES OF FLUROXYPYR AND WHEAT CULTIVAR CHOICE ON THE SEED PRODUCTION, GROWTH AND DEVELOPMENT OF THE PROGENY OF COMMON FIELD SPEEDWELL

G T CHAMPION, R J FROUD-WILLIAMS
Department of Agricultural Botany, The University of Reading, 2 Earley Gate, PO Box 239, Whiteknights, Reading, Berkshire, RG6 6AU, UK

J M HOLLAND
Game Conservancy Trust, Fordingbridge, Hampshire, SP6 1EF, UK

ABSTRACT

Reduced doses of herbicides are now widely being used in cereal crops with little yield penalty. Studies of weeds in these conditions have largely been restricted to the effect of herbicides on weed biomass and hence the weed infestation in the current year. This study was designed to investigate the combined effect of wheat varietal selection and herbicide dose on weed seed production and some qualitative aspects. The largest effect on quality was an alteration in the relative proportions of individual seed size. Herbicide applications increased the proportions of smaller sized seeds at the expense of the larger seeds. Progeny from these seeds showed indirect herbicide effects related to the size of seed from which the plants originated. Implications for future weed infestation are considered.

INTRODUCTION

Recent concerns over environmental issues have prompted much interest and research into practices which reduce agrochemical inputs. This had lead to interest in a systems approach integrating agronomic practices and involved in this technique is the use of reduced herbicide doses. Research has shown that reduced doses of herbicide can provide adequate weed control with yields largely unaffected, although the risks of regrowth may be increased (Fisher *et al.*, 1993). Substantial weed suppression by specific cultivars may occur in certain situations (Whiting *et al.*, 1990) and beneficial interactions of cultivar suppression in conjunction with nitrogen fertiliser use and herbicide application have been reported (Richards, 1993, Christensen, 1994). However, these studies concentrated largely on weed biomass in the present crop as the measure of weed control. Weed seed production and the implications for future years were not considered. Effects on seed production following application of reduced herbicide doses have been considered in a number of weed species (Andersson, 1994) but rarely in conjunction with crop competition.

This study examines weed seed quality and effects on the progeny of *Veronica persica* Poir. (common field speedwell) subject to competition in winter wheat. Seeds were collected following application of full and reduced rates of fluroxypyr applied prior to seed maturation. *V. persica* has good tolerance to fluroxypyr and is checked only at the two leaf stage (Dow Elanco Product Guide 1996/7). In view of the late growth stage at application, effects on seed quality were not anticipated.

MATERIALS AND METHODS

An experiment was designed to investigate the interaction between cultivar, sowing date, nitrogen fertiliser and herbicide dose on weed incidence in an autumn sown winter wheat crop. Two cultivars, Spark and Tonic, were sown on 26 September and 13 October 1994, in a split-plot design with sowing date as the main plot. Plots measured 1.8x6m and received either full (160 kg N ha^{-1}) or half (80 kg N ha^{-1}) the recommended rate of fertiliser as Nitram (34.5% N) in two equal split applications. Each treatment combination was replicated twice making a total of 16 plots. Fluroxypyr (200 g a.i. l^{-1}) was applied as a split-split plot treatment in 1m swaths across these plots on 4 May 1995 at GS 32. Herbicide was applied using an Oxford Precision sprayer at a pressure of 2.1 bar in 200 l/ha at a height of 0.5m above the crop. Rates of one quarter, one half and the full recommended rate (50, 100 and 200g a.i. ha^{-1} respectively) were applied with one untreated swath as a control per plot. Plant material was collected two weeks later from 0.6m swaths in each of the 64 split-split plots.

Plants were separated by species and the reproductive structures removed and counted. Capsules of *V. persica* were counted and where large numbers of capsules were present a sub-sample of 200 was taken for further analysis. Seeds were carefully separated from the capsules and after cleaning were divided into four size categories using Endecotte sieves. The sieves used were of mesh size 500, 710 and 1000 µm. A total of 256 seed samples in the ranges <0.5, 0.5-0.71, 0.71-1 and >1 mm were separated. Few seeds of the smallest size fraction were obtained and these were counted and the samples weighed. The number of seeds present in the larger three fractions were estimated after weighing the total sample and three individual sub-samples each of twenty seeds. Mean seed weight of 100 air dried seeds (mg), average number of seeds per capsule and the percentage of seeds in each of the size classes were calculated.

Samples of each of these seed lots were germinated in Petri dishes and these results reported elsewhere (Champion *et al* in preparation). After germination the seeds were transferred to moist compost in propagation modules. Up to four plants for each treatment size combination were transplanted into John Innes (JI) No. 1 compost in plastic sectional trays of 45x50x50 cm. After 40 days two each of these plants were transplanted into JI No. 2 compost in 85x85x65 cm pots. Plant vigour was assessed by measurement of the main axis length at 10 day intervals up to 50 days after germination.

RESULTS

All the analyses of variance (ANOVA) were performed using the generalised linear models procedure (PROC GLM) in SAS for Windows following appropriate normalising transformation. Means were compared using T tests at the 5% level of significance.

Mean seed weight

The mean seed weight for 100 air dried seeds were calculated for each of the treatment units. Data were square root transformed before ANOVA was performed. Wheat cultivar selection was shown to have a significant effect (P<0.05) on seed weight of *V. persica* (Table 1). Smaller seeds were produced when the *V. persica* grew in the presence of cv. Spark than cv. Tonic. Herbicide rate was also significant (P<0.001) with a negative correlation between seed size and increasing dose of fluroxypyr. The average seed weight of *V. persica* receiving full rate herbicide was reduced by 16% when in competition with Spark and by 8% in the presence of Tonic. There was no interaction between the effects of wheat cultivar and herbicide rate on seed weight.

Table 1. Effect of wheat cultivar and herbicide dose on 100 seed weight of *V. persica* (mg)

	100 seed weight (mg)
Wheat cv. Spark	49.1
Wheat cv. Tonic	53.8
SED between cv. means (31 d.f.)	1.3
0 herbicide (0 g a.i. ha^{-1})	55.2
1/4 herbicide rate (50 g a.i. ha^{-1})	52.3
1/2 herbicide rate (100 g a.i. ha^{-1})	49.6
Full herbicide rate (200 g a.i. ha^{-1})	48.7
SED between 2 herbicide rates (15 d.f.)	1.5

Number of seeds per capsule

The number of seeds per capsule was calculated and ANOVA performed following square root transformation. Herbicide rate significantly reduced (P<0.001) the average number of seeds per capsule at doses above half that recommended (see Table 2). A 17% reduction occurred when herbicide was applied at full rate when compared to the untreated control.

Table 2. Effect of herbicide dose on number of *V. persica* seeds per capsule

Herbicide dose	0	1/4	1/2	1	SED (15 d.f.)
Seeds/capsule	6.38	6.36	5.64	5.29	0.35

Seed size distribution

The number of seeds in each of the four size classes <0.5, 0.5-0.71, 0.71-1 and >1 mm was calculated by weight from three subsamples each of 20 seeds. ANOVA was performed after the data were arc sine transformed. Wheat cultivar and herbicide rate significantly affected (P<0.05 and 0.01 respectively) the percentage of seeds present in the smallest of the size classes (see Table 3). The number of small seeds was greater when *V. persica* grew in the presence of cv. Spark than cv. Tonic and was positively correlated with increasing herbicide dose. Conversely seed size was greater in the presence of Tonic and herbicide was not applied. The percentage of seeds in the 0.71-1 mm range was unaffected by herbicide dose.

There was no interaction between the effects of wheat cultivar and herbicide rate on seed size distribution.

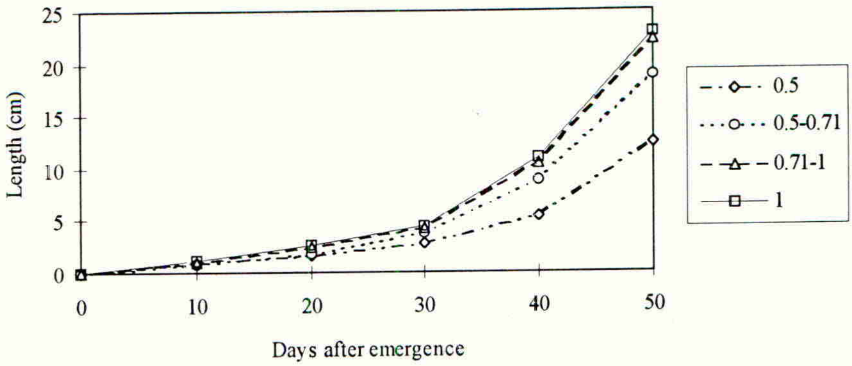
Table 3. Influence of wheat cultivar and herbicide dose on the percentage of *V. persica* seeds in four size classes

Size class (mm)	< 0.5	0.5-0.71	0.71-1	>1
Cv. Spark	5.7	14.0	62.0	18.4
Cv. Tonic	3.8	11.6	59.6	25.0
SED for cv. means (31 d.f.)	0.7	0.9	1.4	1.5
0 herbicide (0 g a.i. ha^{-1})	3.1	9.9	61.9	25.1
1/4 herbicide rate (50 g a.i. ha^{-1})	4.1	11.8	61.9	22.3
1/2 herbicide rate (100 g a.i. ha^{-1})	5.5	14.0	61.2	19.5
Full herbicide rate (200 g a.i. ha^{-1})	6.4	15.5	58.1	20.0
SED between 2 herbicide rates(15 d.f.)	0.9	1.2	2.0	2.1

Plant height

Plant vigour between the seed size classes was assessed by non-destructive means. The length of the main axis was measured at 10 day intervals until 50 days after emergence. Four plants from 10-40 days and two plants at 50 days were measured per treatment, see Figure 1. Mean length data were square root transformed prior to ANOVA. Seed size ($P<0.0001$) significantly affected the length of the main axis until 50 days after emergence. Smaller seeds produced smaller plants. The largest seed classes, 0.71-1 and >1mm, produced similar sized plants but the smallest size class, <0.5 mm, was 46% shorter than those from these two groups. Herbicide rate exerted a significant influence ($P< 0.05$) only at 10 days after emergence. Sowing date and wheat cultivar did not affect the length of the main axis.

Figure 1. Length of *V. persica* progeny main axis in cm.



DISCUSSION

Mean seed weight of *V. persica* was reduced as a result of wheat cultivar competition and herbicide dose. Average seed weight was greater when grown with Tonic than Spark. Biomass of *V. persica*, reported elsewhere (Champion *et al.*, 1995), was also greater under Tonic than Spark. Weed densities were not recorded, but assuming that plant densities were comparable Tonic favours weed growth more than Spark. *V. persica* is very sensitive to shading and exhibits reductions in leaf area and dry weight under reduced light intensity (Fitter and Ashmore, 1974). Reduction of both leaf area and biomass have implications for photosynthesis and hence carbohydrate nutrition. Seed size has been shown to be sensitive to maternal temperature, water availability, resource availability and hormone level (Roach and Wulff, 1987). Thus cultivar competition exerts its influence through reducing nutrient supply and hence resulting seed size is reduced to a greater extent by the more competitive cultivar.

Increases in the rate of herbicide applied reduced both mean seed weight and the average number of seeds per capsule. Differences in number of seeds per capsule appear small, but data quoted on seed production of *V. persica* (Harris and Lovell, 1980) suggest large plants in the absence of competition may produce 565 capsules per plant. In this context reductions of one seed per capsule become more significant for future populations. The reductions in average seed weight with increasing herbicide dose are seen to be related to the increase in the number of the smallest seeds at the expense of the largest sized seeds. Workers studying the effects of other hormone-type herbicides have reported a variety of responses. Andersson (1996) working with MCPA applied at sublethal rates and at a range of application times reported increased seed weight in *Galium spurium* and reduced germination in *Fallopia convolvulus*. He noted that effects were strongly dependent on species and time of application.

Differences in plant height were not related directly to herbicide rate suggesting there was no direct chemical influence on progeny. Other workers have reported strong influences of herbicide use on progeny fitness and particularly in association with fertiliser use (Grundy *et al.*, 1995). In this study height was related to initial seed size from which the plants had originated; thus larger seeds produced larger plants. Herbicide rate shifted the balance of seed size in favour of smaller seeds and thus will then reduce the average size of plants in a population of progeny from herbicide treated plants. Height differences were apparent up to 50 days. Strong linear relationships exist between plant dry weight and dry weight of seeds (Wright, 1993). Size differences, if continued to maturity, are thus likely to result in lower seed production in smaller individuals.

Once shed the weed seeds too will be subject to different pressures on their survival. In studies of persistence of weed seeds in the seedbank, germination was low in the first year following inversion of the soil (Wilson and Lawson, 1992). Only 3-4% of any years seed production was able to emerge in the first two years. This was in a ploughed situation but even shallow incorporation of *V. persica* is likely to result in reduced germination since depth of burial will be more critical for smaller seeds. It is not possible to predict persistence here but it is suggested that larger seeds will survive burial and be able to emerge more easily than smaller ones. Thus survival rates may well be reduced in field situations.

Studies of seed production have concentrated on seed numbers in relation to herbicide effects. However, herbicide effects which influence seed quality in terms of seed weight, seed size and hence dormancy status, germination percentage and progeny fitness have implications for future weed infestations. It has been proposed (Andersson, 1996) and is supported here that seed quality measurements should form an important part of studies on herbicide effects.

ACKNOWLEDGEMENTS

This work was funded by a MAFF CASE award in conjunction with the Game Conservancy Trust.

REFERENCES

Andersson, L (1994) Seed production and seed weight of six weed species treated with MCPA. *Swedish Journal of Agricultural Research*, **24**, 95-100.

Andersson, L (1996) Characteristics of seeds and seedlings from weeds treated with sublethal herbicide doses. *Weed Research*, **36**, 55-64.

Christensen, S (1994) Crop weed competition and herbicide performance in cereals species and varieties. *Weed Research*, **34**, 29-36.

Dow Elanco Product Guide, 1996/7.

Fisher N M; Davies D H K; Whytock G P (1993) Reliability of broad-leaved weed control in cereals using low doses of herbicide. *Brighton Crop Protection Conference - Weeds*, 1223-1228.

Fitter A H; Ashmore C J (1974) Response of two *Veronica* species to a simulated woodland light climate. *New Phytologist.* **73**, 997-1001.

Grundy A C; Froud-Williams R J; Boatman N D (1995) Maternal effects in progeny of field pansy (*Viola arvensis*) subjected to different herbicide and nitrogen rates. *Annals of Applied Biology*, **127**, 343-352.

Harris G R; Lovell P H (1980) Growth and reproductive strategy in *Veronica* spp. . *Annals of Botany*, **45**, 447-458.

Richards M C (1993) The effects of agronomic factors on competition between cereals and weeds; the implications in integrated crop production. *Brighton Crop Protection Conference - Weeds*, 991-996.

Roach D A; Wulff R D (1987) Maternal effects in plants. *Annual Review of Ecology and Systematics*, **18**, 209-235.

Whiting A J; Richards M C; Brown H (1990) Crop competitiveness as an aid to weed control in cereals. *British Crop Protection Council Monograph 45 Organic and Low Input Agriculture,* 197-200

Wilson B J; Lawson H M (1992) Seedbank persistence and seedling emergence of seven weed species in autumn-sown crops following a single year's seeding. *Annals of Applied Biology*, **120**, 105-116.

Wright K J (1993) Weed seed production as affected by crop density and nitrogen application. *British Crop Protection Conference-Weeds*, 275-280.

CARFENTRAZONE-ETHYL : A NEW HERBICIDE FOR THE RAPID CONTROL OF KEY CEREAL BROAD-LEAF WEEDS

S W SHIRES, L A BOURDOUXHE, A R CROSSMAN, B GENOT, J P LAFFRANQUE & J LEBLANC
FMC Europe NV, Avenue Louise 480, 1050 Brussels, Belgium

ABSTRACT

Carfentrazone-ethyl (F8426) is a protoporphyrin oxygenase (PPO) inhibitor that is being developed for the control of weeds in cereals and other crops. Extensive field trials conducted in the major cereal producing countries of Europe have confirmed :

- outstanding activity against *Galium aparine* and some other key cereal broad-leaf weeds, eg *Veronica hederifolia, Lamium purpureum, Sinapis arvensis;*
- very low recommended dose rates (20 g ai/ha);
- rapid action, resulting in weed mortality within a few days after application;
- excellent crop selectivity in small grain cereal varieties.

It is concluded that optimum control of *G. aparine* can be obtained by applying 20 g a.i./ha of carfentrazone-ethyl between crop stages 13 to 32 on weeds ≤20cm high.

INTRODUCTION

Carfentrazone-ethyl (F8426) is a triazolinone protoporphyrin oxygenase (PPO) inhibitor that is being developed as a post-emergence contact herbicide (Van Saun et al., 1993) for the control of key broad-leaf weeds in cereals, maize (Tutt et al., 1995), rice, and grassland. After application to susceptible weeds, carfentrazone-ethyl rapidly penetrates leaf and stem surfaces causing widespread foliar desiccation. Within a few days after treatment, extensive necrosis quickly leads to leaves drying out and finally disintegrating.

Extensive laboratory and field studies have demonstrated that carfentrazone-ethyl has a very low acute and chronic toxicity to mammals, birds, fish and invertebrates. It is also not mutagenic, teratogenic or onchogenic. It is however, toxic to algae and *Lemna*, although adverse effects on such plants following normal commercial applications are unlikely. In soil, water and plants, the parent molecule is rapidly (within 1-3 days) hydrolysed to the chloropropionic acid metabolite, which in turn is quickly transformed to other compounds with little or no herbicidal activity. Carfentrazone-ethyl or its herbicidally active metabolite, do not leach in soil or appear as detectable residues in either grain or straw.

Registrations of carfentrazone-ethyl have already been obtained in several countries, eg. Czech Republic, Poland, Slovak Republic, Switzerland and the UK and approvals in other key cereal growing countries are expected before the end of 1998. In addition, the product is being evaluated for inclusion in Annex 1 of the EU registration directive.

METHODOLOGY

Over 1500 field trials have been conducted with carfentrazone-ethyl in small grain cereals in

Europe during the last 7 years. Key objectives of this work, have been to confirm the crop selectivity, define the weed spectrum, select the optimum dose rates, determine the best application timing and develop premix formulations with key herbicide partners. However, the results reported in this paper refer mainly to trials conducted with a stand-alone carfentrazone-ethyl 500g/kg WG formulation, 'Aurora 50WG', against the principal target weed *G. aparine*. Results obtained against other weeds are reported only in summary format in order to allow a description of the overall weed spectrum of carfentrazone-ethyl.

All efficacy trials were performed in compliance with EPPO guideline No. 93 (Guideline for the biological evaluation of herbicides - weeds in cereals) using a randomised complete block trials design, with either 3 or 4 replicates. The total plot sizes were between 15 and 25 square meters. In all trials, treatments were applied with specialised plot sprayers at an application volume of 200 to 500 liters per hectare. Spray nozzles were selected to give BCPC Medium spray quality. The applications were made at a spray pressure of 1.7 to 3 bar. Mean numbers of weeds per square meter were assessed at the start of the experiments and weed control was estimated at various timings after treatment as a percentage cover using a visual score and/or by counting the number of weeds/m^2.

The crop selectivity of carfentrazone-ethyl 50WG was assessed in three main ways :

- Visual observations of crop selectivity were made on 2 or 3 occasions during the first few weeks after application in all efficacy trials. Any phytotoxicity symptoms were noted and generally recorded as percentage of leaf damage.
- The selectivity of carfentrazone-ethyl to a range of different cereal varieties was also assessed in 26 different trials. The materials and methods employed were essentially the same as in the efficacy trials, except plot sizes were smaller, only 1 or 2 replicates were used and visual assessments were made of percentage crop damage.
- The effect of carfentrazone-ethyl on the yield of small grain cereals was also assessed in 37 field experiments carried out in France, UK and Germany. The materials and methods employed in these trials were similar to those of the efficacy trials, except larger (30 m^2) 'weed-free' plots were chosen and a minimum of four replicates per treatment were used.

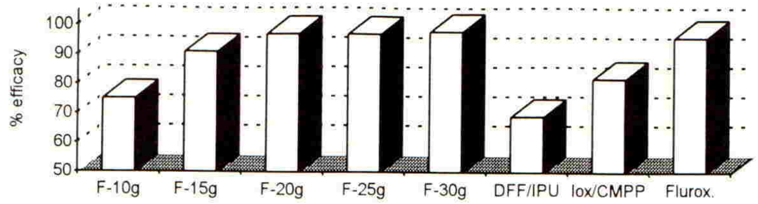
In both the varietal and yield trials, the 1N (15 to 25 g a.i./ha) and 2N (30 to 50 g a.i./ha) dose rates of carfentrazone-ethyl were compared against 'standard' reference compounds.

EFFICACY AGAINST TARGET WEEDS

Galium aparine

Between autumn 1992 and spring 1995 over 150 field trials were conducted in France, Germany and UK to evaluate the efficacy of carfentrazone-ethyl against *G. aparine*. The target dose rate was determined in trials carried out using rates between 10 to 30 g a.i./ha applied from late November to mid April, at crop growth stages between GS 12 to 33. The appropriate 'standard' reference products were used in the same trials, eg. fluroxypyr (200 g a.i./ha), ioxynil/CMPP (360+1080 g a.i./ha), diflufenican/isoproturon (DFF/IPU : 187.5+1500 g a.i./ha). The trials results obtained are summarised in Fig. 1, where it can be seen that there is a sharp increase in efficacy as the dose rate increases from 10 to 20 g a.i./ha. However, further increases in dose rate provided little improvement in the level of control. A target dose for registration of 20 g a.i./ha was therefore selected in order to provide consistent control.

Fig. 1 : Efficacy of different dose rates of carfentrazone-ethyl on *G. aparine*



Standards = IPU/DFF, Ioxynil/CMPP, fluroxypyr F-10g = carfentrazone-ethyl 10 g a.i./ha

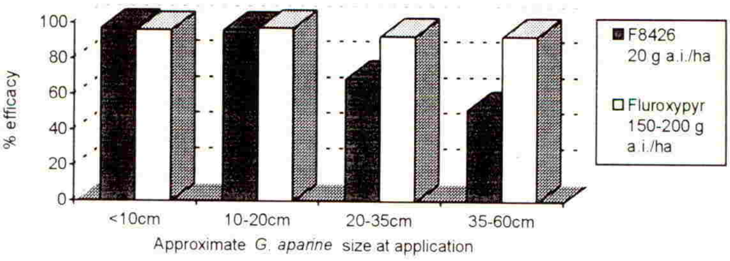
Because carfentrazone-ethyl is a post-emergence contact herbicide, good activity is dependent upon the presence of *G. aparine* at the time of application. Efficacy trials treated from October to January were therefore examined to determine if there were any clear differences in *G. aparine* control with applications made at 3 clearly defined crop growth stages, ie. 2 leaves (GS12), 3 leaves (GS13) and early tillering (GS21). The results (Table 1) obtained demonstrate that greatly improved efficacy can be achieved by avoiding premature application. In fact, the earliest recommended timing for treatment should be at the 3 leaf stage (GS13) of the crop. At this timing, the majority (>90%) of *G. aparine* appears to have emerged in most of the trial locations.

Table 1 : Relationship between crop growth stage (GS) and % efficacy of carfentrazone-ethyl on *G. aparine* in autumn/winter treatments

Crop growth stage	GS12	GS13	GS21
% efficacy	75	93	94

Spray coverage is also a factor influencing the performance of carfentrazone-ethyl. The effect of weed size was therefore investigated in a series of 8 trials involving sequential applications at four different timings, when the mean sizes of *G. aparine* were approximately <10cm, 10-20cm, 20-35cm or 35-60cm. Final assessments of efficacy were made 3 months after treatment. The standard, fluroxypyr, was applied at the same timings. The results obtained (Fig. 2) confirmed that the maximum size of *G. aparine* at the time of treatment should be no

Fig. 2 : Influence of *G. aparine* size on efficacy of carfentrazone-ethyl



more than 20cm. At or below this size, excellent efficacy of carfentrazone-ethyl can be expected, that is equal to the spring applied standard, fluroxypyr.

Since *G. aparine* is a serious problem affecting cereal yields in Europe its rapid and effective control will be seen as a major benefit by farmers. A comparison of the speed of action of carfentrazone-ethyl with that of 'standard' *Galium* products has therefore been carried out using 16 trials conducted in Northern France in 1995 (Table 2). Despite a heavy weed infestation, all products used in these trials achieved an outstanding (99%) long-term efficacy against *G. aparine*. However, carfentrazone-ethyl distinguished itself by providing the fastest speed of action, with 87% of the GALAP destroyed only one week after application and 96% within two weeks (Table 2). In contrast, the other products gave only limited effects (11-36%) in one week and it took about eight weeks for both fluroxypyr and amidosulfuron to achieve the same efficacy as carfentrazone-ethyl did in the first week. The same results were also observed following autumn applications, with carfentrazone-ethyl giving 93% control of *G. aparine* in the first 2 weeks, compared with only 17% control with a IPU/DFF mixture.

Table 2 : % control of *G. aparine* with carfentrazone-ethyl at different intervals after application, compared with spring and autumn applied 'standard' products

Treatment	**Dose rate g a.i./ha**	**Spray Timing**	**Number of weeks after application**			
			1	**2**	**4**	**8 to 16**
Carfentrazone-ethyl	20	spring	87	96	99	99
Fluroxypyr	200	spring	19	66	93	99
Amidosulfuron	30	spring	11	58	88	99
Ioxynil/CMPP	360+1080	spring	36	80	97	99
Carfentrazone-ethyl	20	autumn	-	93	98	93
IPU/DFF	1500+187	autumn	-	17	53	87

Other Broad-leaf Cereal Weeds

Results obtained in over 1,000 trials conducted in north, south, west, central and east Europe have provided a good understanding of the activity spectrum of carfentrazone-ethyl. The weeds controlled at different dose rates are summarised in Table 3. Weeds notably resistant to carfentrazone-ethyl include *Stellaria media* and *Matricaria spp.* However, experience has shown that these weeds are readily controlled by mixing carfentrazone-ethyl with other herbicides such as IPU, phenoxies and/or sulphenyl ureas.

CEREAL CROP SELECTIVITY

In over 200 efficacy trials in cereals with carfentrazone-ethyl (50WG), visual observations of crop selectivity were made on 2 or 3 occasions during the first few weeks after application. In 96% of the trials, either no symptoms or only very minor (1-5%) phytotoxicity was observed. Of the 4% remaining trials, the maximum recorded phytotoxicity did not exceed 10%, except on one occasion with a very late application made at the booting stage of the crop. In all of the other trials, no major differences in selectivity were observed when applications were made between the 1 leaf (GS11) to second node (GS32) crop stage. In addition no differences in selectivity were observed between wheat or barley and winter or spring sown crops.

Table 3 : Effective dose rate of carfentrazone-ethyl needed to control (≥90%) susceptible European broad-leaf weeds

Effective dose rate of carfentrazone-ethyl (50WG)		
5 - 10 g a.i./ha	10 - 20 g a.i./ha	20 - 30 g a.i./ha
Solanum nigrum	*Galium aparine*	*Veronica persica*
Abutilon spp.	*Veronica hederifolia*	*Thlaspi arvensis*
	Capsella bursa-pastoris	*Cyperus spp*
	Lamium purpureum	*Raphanus raphanistrum*
	Amaranthus retroflexus	*Xanthium spp.**
	Chenopodium album	*Bifora radians**
	Mercurialis annua	
	Sinapis arvensis	
	*Papaver rhoeas**	
	*Viola arvensis**	
	*Fallopia convolvulus**	
	*Polygonum persicaria**	
	*Cirsium arvensis**	
	*Sonchus arvensis**	

* maximum weed size = 2 to 4 leaves

In the varietal susceptibility trials, 90 winter wheat, 58 winter barley and over 35 other varieties of spring wheat, spring barley, oats, durum wheat, rye and triticale were tested in France and UK alone. The results (Table 4) demonstrate that 75% of all varieties showed no phytotoxic symptoms when carfentrazone-ethyl was applied at the 1N target dose rate (20 g a.i./ha) and a further 24% showed only very minor (1-5%) symptoms of transient necrotic leaf spotting. Even at the 2N dose rate (40 g a.i./ha), 94% of all varieties had either no symptoms or very minor (<5%) necrotic spotting of the leaves. Only one result of unacceptable phytotoxicity (>15%) was recorded. Overall, the selectivity of carfentrazone-ethyl (50WG) to a range of cereal varieties was superior to the French 'official reference' product (a premix of ioxynil/CMPP) and one of the UK 'standards' (a premix of bromoxynil/ioxynil/fluroxypyr).

Table 4 : Percentage of cereal varieties showing different ranges of phytotoxicity following the application of carfentrazone-ethyl (50WG)

		% necrotic spotting on leaves				
Product	dose rate	0%	1-5%	6-10%	11-15%	>15%
F8426	N	75	24	0.6	0.4	-
	2N	56	38	5.6	0.2	0.2
'Standard'	N	54	35	4.3	4.1	2.6
	2N	60	20	2.0	15	3.0

It is important to note that any symptoms of injury after the application of carfentrazone-ethyl (50WG) were always typified by transient necrotic spotting of the leaves which disappeared within 1 to 3 weeks after spraying.

Results from yield trials also confirmed the excellent selectivity of carfentrazone-ethyl, with no effects being observed after autumn or spring applications on wheat or barley (Table 5).

Table 5 : Mean grain yields (MT/ha) from plots treated with carfentrazone-ethyl (50WG)

Timing	Crop	# trials	carf. 1N	carf. 2N	std. 1N	std. 2N	untr.
autumn	ww	6	8.4	8.3	8.4	8.4	8.3
autumn	wb	4	7.5	7.7	7.8	7.6	7.6
spring	ww	16	7.7	7.7	7.8	7.6	7.6
spring	wb	11	6.0	5.9	6.0	6.1	6.0

ww = winter wheat, wb = winter barley, carf. = carfentrazone-ethyl, ref. = 'standards', untr. = untreated

CONCLUSIONS

Carfentrazone-ethyl demonstrates excellent selectivity to cereal crops. It should be used at 20 g a.i./ha, to provide rapid control of *G. aparine* and several other important broad-leaf weeds, such as *V. hederifolia*. Applications can be made in autumn or spring from the 3 leaf (GS13) to the second node (GS32) stage of the crop. Optimum efficacy is obtained by treating *G. aparine* ≤20cm tall and most other weeds at early growth stages. The above features make carfentrazone-ethyl an ideal mixture partner for a range of other cereal herbicides where it can complement the weed spectrum, speed of control and mode of action. Several such mixtures have already been developed and will be commercialised in cereal growing countries over the next few years.

ACKNOWLEDGEMENTS

The authors would like to thank other FMC colleagues for their valuable contributions.

REFERENCES

Van Saun, W A; Bahr, J T; Bourdouxhe, L A; Gargantiel, F J; Hotzman, F W; Shires, S W; Sladen, N A; Tutt, S F; Wilson, K R (1993) F8426 - a new, rapidly acting, low rate herbicide for the post-emergence selective control of broad-leaved weeds in cereals. *Brighton Crop Protection Conference Proceedings, **2-1**, 19-22*

Tutt, S F; Bahr, J T; Hotzman, F W; Van Saun, W A; Bourdouxhe, L A; Shires, S W; Casey, J S; Hatfield, L D; Mize, T W; Thayer, J M (1995) F8426 - a new, low rate herbicide for the post-emergence selective control of broadleaf weeds in maize. *Brighton Crop Protection Proceedings, **6C-18**, 731-736.*

SESSION 3B

WEED CONTROL IN HORTICULTURE

Chairman and Session Organiser	MS C M KNOTT *Processors & Growers Research Organisation, Peterborough, UK*
Papers	3B-1 to 3B-5

RECENT DEVELOPMENTS IN THE MANAGEMENT OF THE REDUCING PORTFOLIO OF PLANT PROTECTION PRODUCTS AVAILABLE TO EUROPEAN PRODUCERS OF MINOR CROPS

C J C WISE
National Farmers' Union, Agriculture House, 164 Shaftesbury Avenue, London, WC2H 8HL, UK

P J CHAPMAN
Pesticides Safety Directorate, Mallard House, Kings Pool, 3 Peasholme Green, York, YO1 2PX, UK

ABSTRACT

This paper provides an update on recent activities designed to address the problems associated with the management of minor use authorisations in the UK and Europe. It outlines some new initiatives designed to facilitate the authorisation pesticides for use on minor crops. In particular it reports on developments in the communication of availability of Specific Off-label Approvals (SOLAs) in the UK and on the establishment of international working groups.

INTRODUCTION

Any paper reviewing the management of problems concerning the authorisation of pesticides for use on minor crops is prone to repeat what has been written before. The reasons behind the problems show no signs of abating.

The present UK position was summarised by Chapman and Kyle (1996), detailing the regulatory mechanisms implemented in respect of 'authorised extensions of use'. These mechanisms are consistent with the provisions of Article 9 of Directive 91/414/EEC, (Anon 1991). However the interpretation and implementation of this facility currently varies between different Member States. In time it is possible that Mutual Recognition under Article 10 of the Directive, which will enable authorisations granted one Member State to be recognised in another, may provide the means by which authorisations for minor crops can become more generally available. A prerequisite of Mutual Recognition is the listing of the active substances involved on Annex I of the Directive. The first such listings will occur in late 1997. In the meantime there is a need to seek alternative means to determine whether there are means of authorising uses in minor crops which are available elsewhere, without compromising consumer, user and environmental safety. This depends very much on developing and improving liaison between the regulators, approval holders and growers in different Member States. Improved information flow at both national and European levels will be an essential part of any satisfactory solution.

It has been suggested that the UK model for minor use authorisation, based on the style of the liaison activities of the British Crop Protection Council's (BCPC) Minor Uses Committee, be extended on an European basis. To a degree this has been achieved, but the introduction of Directives to harmonise Maximum Residue Levels (MRLs) has accelerated the need for greater liaison and exposed the inability of grower groups within Member States to respond within allotted time-frames. Although time is given in these Directives for grower groups to generate residue data to Good Laboratory Practice (GLP) standards for the accepted good agricultural practice, it still remains difficult to orchestrate such activities. Consequently the impact of these Directives is now being felt at grower level.

Growers are experiencing loss of uses on minor crops and complete revocation of certain products which hitherto have been essential for specialist crop production. The Dutch have estimated that up to 30% of uses have been lost in recent years. Undoubtedly the long reaching effects have concentrated the minds of growers especially in European countries that rely heavily on exports of fresh produce. The increasing influence of the legislative food safety requirements of Germany and the UK (which are the major importing markets) are directly influencing growers and produce marketing organisations. Additionally the lack of MRLs for specific pesticide/fresh produce combinations means that treated fresh produce cannot be legally traded. The requirement for due diligence placed upon multiple retailers, who account for an ever increasing proportion of food supply to consumers, to purvey food that is safe, wholesome and produced in an environmentally sensitive manner, is also beginning to exert commercial influence and awareness.

DEVELOPMENTS IN THE UK

Under the MRL-setting Directives, various uses of cypermethrin and chlorpyrifos have already been revoked. This has had a profound effect on British growers of carrots, swedes, and the speciality crop; white turnips. The situation has also been exacerbated by the withdrawal of chlorfenvinphos granules for commercial reasons. The control of pests (especially cabbage root fly) and diseases in minority crops such as white turnips, needs clear and careful study especially in view of the increased consumer concern over the use of organophosphorus materials. In order to make day to day progress with the management of such crops, British growers need to know what is available for legal use on the continent. There is a need for fast and accurate dissemination of all available information and use of modern information technology may assist in reaching this objective.

For many years the National Farmers Union (NFU) and the Horticultural Development Council (HDC) have been responsible for the co-ordination on 'specific authorised extensions of use' (called specific off-label approvals or SOLAs). Together with Campden and Chorleywood Food Research Association, the NFU has built up the only dedicated database of SOLAs in the public domain. This database is now available to growers in an electronic form from the 'Rural Business Network' using 'Farming On Line' as the service provider.

Growers are now able to interrogate this database to find out what products are specifically approved for use on the crops of interest to them. Negotiations are currently underway with PSD to extend the information provided to incorporate the text of the specific ‘Notice of Approval’ documents. It is hoped that in future growers will be able to access these documents directly on line and print them locally. It is an offence under the Control of

Pesticides Regulations, for a grower who is proposing to use a product under a specific authorised extension of use not to comply with the conditions laid down in the 'Notice of Approval'. Therefore growers must be in possession of, and have read, the appropriate document, before using the plant protection product. Historically PSD, the Agricultural Development Advisory Service (ADAS) and the NFU have been largely responsible for the dissemination of hard copies of these documents to growers.

The core information contained in the database is derived directly from PSD but the database's interface is designed to be 'grower friendly'. It became available on-line in September, 1997. This database will also be available to the multiple retailers and food processing sectors and it is planned to extend the database in 1998 to include the information on MRLs. It is hoped that this development in information technology will lead the way to a similar on-line pan-European database.

DEVELOPMENTS AT THE EUROPEAN LEVEL

Over the last three years two parallel initiatives have progressed within Europe.

Liaison between Regulatory Authorities

Under the sponsorship of the German regulatory authority (BBA), European regulators have come together for two international symposia on minor uses. These occurred in 1993 and 1996 and were attended principally by representatives of northern Member States. In addition representatives of the United States Inter-regional Project 4 (IR-4) attended, as did members of the European Commission (EC). The proceedings of both these symposia have been published by the BBA (1993, 1996). The purpose of these symposia was to share experiences in addressing the problem of the authorisation of pesticide uses in minor crops and to explore the possibilities for co-operation in this area. It is hoped that any mechanism developed by the participants to assist in the authorisation of uses for minor crops could be adopted by other Member States. A series of work-shops within the 1996 symposium developed a number of recommendations to propose solutions to the most fundamental questions. It was agreed that two working groups should be established.

The first group is working on the development of an international database of minor uses, as a first step it was suggested that an overview of the most important problems on minor crops should be prepared. The German regulatory authority has taken the lead on this project and has invited supplementary information from all participating Member States.

The second working group has been set up to consider the possibilities of a harmonised approach to the problem of authorisation of minor uses. This group has been established as an Expert Group under the EC Legislation Working Group. European farmers and growers (under the umbrella of the Committee of Agricultural Organisations (COPA)/General Committee for Agricultural Co-operation (COGECA) and manufacturers (as the European Crop Protection Association (ECPA) and the European Crop Care Association (ECCA), have also been invited to participate. The group is currently working on the following areas:

The definition of a minor use - there is consensus that all uses in minor crops as well as certain uses in major crops should be defined as minor uses. Although COPA/COGECA feel that national authorities should be left with the necessary flexibility to interpret what constitutes a minor use in the area for which they are responsible; it was agreed that a list of examples would be helpful.

Efficacy requirements - data on efficacy should be obtainable from as many sources as possible. The European Plant Protection Organisation (EPPO) are in the process of drawing together guidance in this area.

Residue data requirements - guidance on permitted extrapolations has been circulated by the European Commission. It was agreed that further flexibility based on sound scientific principles should be sought for establishing MRLs for minor crops. It is felt that the residue data requirements for very minor crops (e.g. herbs and spices which are not consumed in significant volumes) should be identified as requiring specific *ad hoc* solutions.

Liability - Liability laws vary between Member States. Although the authorised extensions of use as practised in the UK provides a working basis for progress in this area, some Member States believe that, irrespective of whether authorisation is granted on or off-label, the provision of an official document setting out conditions of use renders the manufacturer liable. It was agreed that Legal advice is required in this area.

Data protection - COPA/COGECA has not finalised its position on the status on the protection of data generated by grower groups within Member States. Some Member States argue that Article 13 of the Directive on data protection does not apply to extensions of use. The Commission have agreed to check in detail how data protection might apply, distinguishing between manufacturers, growers or national authorities as data holders. COPA's position on data protection indicates that data generated by growers groups should remain their property and should be subject to an element of data protection. In general terms it is felt that these data should not be fully protected for a set period but should be available for supporting authorisation in other Member States provided recompense is made to the data owner. In practical terms this means that growers groups in one Member State can recognise data held by a grower group in another Member State provided it recompenses that grower group appropriately.

Registration of minor uses - the Expert Group is discussing a draft protocol which provides a common framework mechanism by which minor uses can be evaluated for authorisation in individual Member States.

Exchange of information - the working group has considered how information should be exchanged between grower groups in different Member States. COPA/COGECA support the concept that a single rapporteur regulatory authority should be appointed amalgamating the review of the active substance under Directive 91/414 with the setting of MRLs for that compound. If this was the case, it would be appropriate that the management of the provision of data to enable MRLs to be set, including growers' groups intention to support, be co-ordinated by the rapporteur regulatory authority.

Liaison amongst European Growers

Mirroring these activities, European farmers and growers have set up liaison groups under the umbrella of COPA/COGECA. These sector-specific liaison groups are attempting to identify the pan-European needs and also to resolve particular difficulties in their commodities. For example, where good agricultural practice (GAP) for the use of a pesticide differs between Member States, the GAP used in setting the MRL will be from the Member State where the critical GAP exists; critical GAPs may be identified separately for northern and southern Europe.

In the UK, manufacturers were requested to confirm to the regulatory authorities which 'open positions' are being supported either by trials or by data submitted to the EC Review programme so that PSD could inform grower groups of the current position and give them an opportunity to generate the necessary data. UK growers expressed disquiet that data developed by them could be used to benefit growers elsewhere Europe who have not made any contribution to the cost of obtaining the data.

The initial efforts by COPA to address the MRL/open positions issue have been applauded by certain regulatory authorities. Clearly the activities of European grower groups must dovetail and, the unnecessary duplication of residue trials to the critical GAP must be avoided. COPA's working groups must address the issue of how to organise sharing the funding of grower-sponsored residue trials.

Typical liaison difficulties being experienced by European growers are exemplified by the position of chlormequat on pears. The MRL for chlormequat on pears is an 'open position' in the MRL-setting Directive (i.e. data are required to be generated and evaluated in order to set an EC MRL). UK growers have no legal access for this use, but treatment is widespread in the major pear growing areas of Netherlands and Belgium. This authorisation is likely to fall in two years time when the MRL defaults to the "limit of determination" unless grower groups are prepared to fund trials.

UK growers are now attempting to inform their overseas counterparts that they see no reason why they should fund this work although they would like access to the use but because of difficulties in communication it is believed that overseas growers are unaware that this use is likely to be lost. It is only by information from British growers and PSD that they have been alerted to this possibility. Some commentators argue that individual Member State regulatory authorities have an duty of care to inform their growers of the likelihood that such key uses may be lost.

SUMMARY

The full harmonisation of pesticides regulation in the European Union under Directive 91/414/EEC will take many years to accomplish. As yet it is unclear how effective the operation of Mutual Recognition of authorisations between Member States will be, particularly in respect of minor uses. Regardless of such developments it is clear that with the passage of time pesticide manufacturers are becoming increasingly reluctant to support minor uses on their product labels. There are a variety of reasons for this situation arising, including the necessity for the establishment of a MRL for each particular pesticide/crop combination and the problems of product liability for small area, high value crops. This situation has prompted regulators, representatives of the grower industry and the pesticide producers to come together to seek means of communication and co-operation within the spirit of Directive 91/414, to develop solutions which can spread the burden in terms of generating the necessary data, or indeed making existing data available for use in support of regulatory decision making.

REFERENCES

Anon. (1991) Council Directive 91/414/EEC of 15 July 1991, concerning the placing of plant protection products on the market. *Official Journal of the European Communities*, L 230.

BBA (1993) *International Symposium on Minor Uses 1993, Braunschweig*, (eds H-H Schmidt and A Holzmann), pp. 93-101. Parey, Berlin and Hamburg. ISBN 3-489-29100-X.

BBA (1996) *2nd International Symposium on Minor Uses 1996, Berlin*, (eds W Pallutt and H-H Schmidt), pp. 92-97. Parey Buchverlag, Berlin. ISBN 3-8263-3129-X.

Chapman, P J; Kyle H (1996) 'Minor uses of plant protection products in the UK: Where are we now? In *2nd International Symposium on Minor Uses 1996, Berlin*, (eds W Pallutt and H-H Schmidt), pp. 92-97. Parey Buchverlag, Berlin.

THE VALUE OF OLDER HERBICIDES FOR VEGETABLE CROPS IN CALIFORNIA

C E BELL
University of California Cooperative Extension, 1050 E. Holton Road, Holtville, California 92250, USA

ABSTRACT

Most of the herbicides used on vegetable crops in California, USA are more than 20 years old. Vegetable farmers in California rely on these herbicides to maintain the economic vigor of a industry worth $5,6 billion in 1995. Registration of new herbicides for vegetables has not kept pace with major crops, such as maize, wheat, or cotton, for a variety of reasons, mostly relating to registration costs and liability issues. Although publicly funded programs can assist vegetable farmers with herbicide registrations for minor crops, the agrochemical industry and regulatory agencies are encouraged to recognize the situation of vegetable farmer with regard to herbicides and maintain existing registrations while developing new herbicides for vegetables.

INTRODUCTION

The development of new herbicides is vital to agriculture for a number of reasons. The newer herbicides, such as the sulfonylureas and imadazilinones, are effective at very low usage rates compared to older herbicides. Public safety characteristics of newer herbicides, both with regard to human health and environmental contamination, are greatly improved. The registration of newer, "safer" herbicides is a regulatory priority in the US (Andersen *et al.*, 1996). Maize, wheat, cotton, and soyabean farmers have had the benefit of these new herbicides. These benefits have not been extended to farmers of minor crops, such as vegetables. The importance of older herbicides in vegetable crops, therefore, remains very high. Examples of these herbicides are bensulide in lettuce and melons; trifluralin in solanaceous and umbelliferous crops; linuron in carrot, parsnip, and celery; and chlorthal-dimethyl in onions, garlic, brassicas, and melons. The youngest of these herbicides, chlorthal-dimethyl, was first approved for use in the US more than 25 years ago.

Over 150 types of vegetable crops are grown in California with gross sales in 1995 of $5 560 000 000 (Anon, 1996). Vegetable crops account for 24.3% of all farm income for 1995 in California and makes an important contribution to the overall State economy in jobs and income. Without adequate herbicides, California vegetable farmers would not be able to maintain their competitive ability in the marketplace. This paper will delineate the amount of older herbicides utilized by farmers of vegetable crops, discuss some reasons why new herbicides are not being registered for use in vegetables, describe a national program in the US that works to obtain pesticides for minor crops, and discuss new US federal law that affects pesticide registrations of minor crops.

HERBICIDE USE IN VEGETABLES IN CALIFORNIA

For this discussion, herbicide use in seven vegetable crops or crop groups will be illustrated. These crops are asparagus, cole crops (cabbage, broccoli, cauliflower, and Brussels sprouts), carrot, lettuce, cucurbits (melons, cucumber, pumpkin, and squash), onion, and tomato. Table 1 lists these crops, the area planted, their gross sale value in 1995, and their contribution to total US production of these crops. All of these are important vegetables grown in California, accounting for 67% of the vegetable market in the State. In several cases, California production of these vegetables accounts for the majority of the US market availability. These are also common vegetable crops in Europe, which should make this information relevant to this conference.

Table 1. Statistical information on selected vegetable crops grown in California, USA in 1995.

Crop or crop group	Hectares	Gross value ($US)	US production %
Asparagus	11 336	91 728 000	38
Carrot	25 709	287 000 000	55
Cole Crops	59 514	581 132 000	87
Cucurbits	43 929	482 193 000	25
Lettuce	78 947	1 263 000 000	72
Onion	15 385	130 666 000	25
Tomato	132 510	865 360 000	87
Total	367 330	3 701 079 000	

Table 2 shows the herbicides used in these crops in 1995, the year the herbicides were first approved by the federal government, and the number of hectares treated. Under California pesticide regulations adopted in 1991, all agricultural pesticide use is reported and compiled by the state. These data came from internet websites maintained by the California Department of Pesticide Regulation (www.cdpr.ca.gov) and the US Environmental Protection Agency (www.cdpr.ca.gov/docs/epa/m2.htm).

The newest herbicides on Table 2 are the selective grass herbicides; clethodim (the only one with a registration in the 1990's), sethoxydim, and fluazifop. Except for onions, the grass herbicides are not used on a large percentage of vegetable crops where they are registered. In most cases, California farmers are relying on herbicides over 30 years old. Two major herbicides for asparagus, diuron and linuron, are both over 36 years old. Carrots in California are grown at very high densities of 2,5 million plants per hectare, too dense to use mechanical cultivation or hand weeding. Where would carrot growers be without linuron and trifluralin? Organic carrot growers in California routinely spend $2500 to $5000 per ha for handweeding, compared to about $80 per ha for linuron and trifluralin.

Chlorthal-dimethyl, another old herbicide, is the most widely used herbicide on cole crops. This herbicide is also a major contributor to weed control and high crop yield of onions. The recent announcement by the manufacturer of chlorthal-dimethyl to discontinue production in the US is causing a lot of worry to farmers, especially onion growers. With the loss of chlorthal-dimethyl, onion farmers will be left with bromoxynil (39 years old) and oxyfluorfen (a youngster at 18 years). Possible substitutes for chlorthal-dimethyl are bensulide and metolachlor, neither of which would be considered a new herbicide.

Table 2. Herbicide use in vegetable crops in 1995 in California, USA.

Herbicide		% of crop treated[a]						
	Year[b]	Asp[c]	Car	Cole	Let	Cuc	Onion	Tomato
benfluralin	1965				13.5			
bensulide	1968			1.4	4.9	9.5		<0.1
bromoxynil	1965						99.3	
chlorthal-dimethyl	1970			62.4		1.4	59.5	<0.1
clethodim	1992						12.3	
dicamba	1962	1.0						
diuron	1958	48.2						
EPTC	1958		2.0	0.5	0.2			4.7
ethalfluralin	1983					8.4		
fluazifop	1983	<0.1					37.3	
glyphosate	1974	56.7	2.0	1.0	1.9	15.1	13.3	50.2
linuron	1961	52.4	135.7					
metham sodium	1969	0.1	45.9	3.0	1.8	12.8	6.0	23.7
metolachlor	1978							<0.1
metribuzin	1973	19.1						15.9
napropamide	1974	1.8		1.3				32.5
norflurazon	1977	10.6						
oxyfluorfen	1979		0.9	20.8	<0.1	7.0	176.0	
paraquat	1966	11.9	0.5	0.6	1.1	6.4	0.9	8.0
pebulate	1961							25.6
pendimethalin	1975						29.0	
pronamide	1972				77.1			
sethoxydim	1982	3.6		0.9	0.3	6.4	8.6	7.0
simazine	1958	8.4						
trifluralin	1966	17.1	76.4	4.3		19.5	2.6	65.3

[a] Blank sections indicate there is no registration for that herbicide/crop combination. Percentages greater than 100 indicate more than one herbicide application per season. Total hectares for each crop are shown in Table 1.

[b] Year first approved in the US, not necessarily on that crop.

[c] Asp = asparagus, Car = carrot, Cole = cole crops (cabbage, broccoli, cauliflower, Brussels sprouts), let = lettuce, cuc = cucurbits (melon, cucumber, pumpkin, squash).

REASONS FOR LIMITED HERBICIDE REGISTRATIONS IN VEGETABLES

There are several reasons why herbicide registrations are so limited on vegetables. Probably the most important reason, the one most often cited, is the cost and liability factor (Klingmann & Ashton, 1982). Herbicide registration costs on a vegetable are so high that it takes several years of sales on the crop to return a profit. In the meantime, one case of herbicide injury on 40 hectares of a high value vegetable such as tomato, followed by a lawsuit with a judgment in favor of the farmer, can cost a chemical company several years profit. Another reason is crop safety. Table 2 illustrates the wide array of herbicides needed to control weeds in only seven crops or crops families. This is not because of weed control, several of these herbicides control the same weeds, but because of herbicide selectivity on vegetable crops. The differential sensitivity of lettuce to two closely related dinitroaniline herbicides, benfluralin and trifluralin, is a good example. This is a continuing problem for the new herbicides. Weather, soil, and climate also influence herbicide selectivity. Halosulfuron, for example, can be used safely on most cucurbit crops in the Southeastern US, but not in the West.

Two more possible reasons for limited herbicide registrations on vegetables are the small amount, relative to insecticides, of weed resistance and the efficacy of available herbicides. Although weeds do develop resistance to herbicides, it does not happen quickly (Gould, 1995). In vegetable growing regions, like California, the high diversity of crops and the frequent rotations help to delay or prevent weeds from becoming herbicide resistant. Agricultural chemical companies do not have the same urgency to find replacement herbicides as they do with insecticides. The efficacy of existing vegetable herbicides is also a disincentive to the introduction of new products. How much of a market share, especially an already small market, can a manufacturer expect with a new carrot herbicide that has to compete with trifluralin or linuron, two very effective and inexpensive herbicides? Only when a herbicide is lost, as in the case of chlorthal-dimethyl in the US, do manufacturers feel inclined to register their herbicides to fill the vacancy.

INTERREGIONAL PROJECT 4

Interregional project 4, commonly known as IR-4, was created in 1963 by the Directors of the Agricultural Experiment Stations of the State Land-Grant Universities to help in registration of pesticides for minor crops. Pesticide tolerances, the amount of the chemical allowed to be present in the crop at harvest, is required for every crop (or crop group) on which that pesticide is used in the US. The IR-4 program coordinates and funds pesticide residue studies to establish tolerances for minor crops. Tolerance applications are submitted to the US Environmental Protection Agency (US-EPA). After the tolerance is established, the manufacturer is expected to get the registration for use on the crops tested. IR-4 receives funding and administration from the US Department of Agriculture, but functions through Universities in the 50 States. Annually, university scientists and extensionists in pest management meet with agricultural chemical company scientists, representatives of farmer organizations, and IR-4 staff to determine priorities for testing. IR-4 has also been instrumental in working with US-EPA to create crop groupings, such as root and tuber crops or leafy vegetables, that allow tolerances developed on representative crops to apply to the group. Since its inception, IR-4 has been responsible for over 4 000 new tolerances on minor crops and has been cited as an example of teamwork between Federal agencies, State agencies, and private industry.

THE US FOOD QUALITY PROTECTION ACT OF 1996

The Food Quality Protection Act (FQPA) became effective the day it was signed by President Clinton in August, 1996. It is a complicated law with many conflicting provisions, the impacts on pesticide use in the US are not understood at this time. This law does have a minor crop section, the first time minor crops are cited specifically in federal legislation. Minor crops are defined as those having less that about 120 000 ha total production in the US. This includes all but 26 crops in the country, but it does exclude grapes, tomatoes, and potatoes, crops traditionally regarded as minor. Special incentives are provided to agricultural chemical companies to register pesticides on minor crops. Other provisions of the law, not dealing directly with minor crops, but those concerning reviews of existing pesticides and limits to overall tolerances, may remove many of the older pesticides from the market. Only time will tell what the long term effect of FQPA will be on the availability of pesticides for minor crops, but the situation is not viewed optimistically at this time by fruit and vegetable growers.

CONCLUSION

Agriculture is more than the production of maize, soyabean, wheat, and rice. The agricultural chemical industry should be encouraged to continue to support older herbicides for horticultural crops that occupy limited hectares, while devoting resources to develop newer herbicides for these crops. The scientific and regulatory communities also should recognize the value of these older herbicides, the difficulties faced by farmers when trying to find modern replacements for vegetable crops, and not be in such a hurry to get rid of these valuable herbicides.

REFERENCES

Anon. (1996) California Agricultural Resource Directory. California Department of Food and Agriculture, Sacramento, California, USA

Andersen, J; Leslie, A; Matten, S; Kumar, R (1996) The Environmental Protection Agency's program to encourage the use of safer pesticides. *Weed Technology*. **10**, 966-968.

Gould, F (1995) Comparisons between resistance management strategies for insects and weeds. *Weed Technology*. **9**, 830-839.

Klingmann, G C; Ashton, F M (1982) *In* Weed science: principles and practices (second edition) John Wiley & Sons, New York, pp. 332-333.

HERBICIDE MOVEMENT FROM CONTAINER GROWN ORNAMENTAL PLANT PRODUCTION NURSERIES

J A BRIGGS, T WHITWELL
Department of Horticulture, PO Box 340375, Clemson University, Clemson, South Carolina, USA 29634-0375

ABSTRACT

Pesticides may move from application site in run-off water during containerized plant production. Vegetated filter strips have proven to be efficacious in pollutant removal from run-off and waste waters. A pulsed irrigation regime reduces run-off volume and pollutants in leachates. In two studies, granular isoxaben and trifluralin were applied to growing beds at a commercial plant nursery. In the first study, run-off water was channelled into waterways of clay/gravel or hybrid Bermuda grass. Isoxaben was detected in run-off water through four days after application. Trifluralin was detected only on the day of application. Amounts lost as a percent of total applied were 23% isoxaben from both waterways. Less than 0.01% of applied trifluralin was detected. The grassed waterways reduced losses of isoxaben by 16% on the day of application. In the second study, pulsed irrigation (3-30 minute cycles) was combined with channelling of run-off water into grass waterways to determine the effects on isoxaben and trifluralin amounts in run-off. Volume of run-off water from the pulsed treatment was 85% of that from continuous irrigation. The herbicides were detected on the day of application in both treatments. Isoxaben was detected through 8 days after application from both treatments. Concentrations and amounts of isoxaben were reduced by the pulsed irrigation/grass waterway treatment on the day of application and as a total for the study. The results indicate that vegetated waterways and pulsed irrigation can reduce herbicide losses from application site in run-off water.

INTRODUCTION

The potential for movement of a herbicide in run-off water is determined by the physical and chemical properties of the compound, application methods, and environmental and climatic conditions. Herbicides which are lipophilic and/or persist in the environment are most likely candidates for transport from site. The flow rate of run-off is a critical factor in determining losses with amounts detected increasing with water application intensity (Schreiber *et al.*, 1993). Highest concentrations of pesticide are consistently detected in the first run-off event after application (Keese *et al.*, 1994). Smaller losses are found as the length of time between application and a run-off generating event increases (Gaynor *et al.*, 1995). Impediments to irrigation or rainfall penetration in soils, such as antecedent soil moisture, vegetation residues, or impermeable surfaces, result in greater losses of pesticides (Shaw *et al.*, 1992).

The containerized nursery industry embraces a unique set of management systems which encourage the movement of herbicides in run-off water. Production practices include overhead irrigation systems (typically 30% efficient), utilization of semi- or impermeable ground covers as a base for growing beds, and a reliance on herbicides to reduce weed competition. Broadcast applied granular herbicides cover foliage, pots, and ground covers and are available for transport from application site in the run-off waters generated by overhead irrigation. Herbicides have been detected in run-off water and containment pond water and sediments at container nurseries (Keese *et al.*, 1994; Riley *et al.*, 1994). Isoxaben amounts totalling 13% of the applied volume were found to move from application site within

5 days of application at a container nursery (Wilson *et al.*, 1996). Collection and containment of run-off water pose the possibility of reintroduction of pollutants onto the growing beds resulting in crop injury.

The utilization of vegetated filter strips contiguous to agricultural fields results in a reduction of the transport of pesticides in run-off water (Dillaha *et al.*, 1989). The mechanism of effectiveness is primarily a reduction in the volume and transport capacity of the run-off water allowing for greater infiltration. Atrazine removal by grassed, predominantly *Bromus inermis* filter strips of various length, was investigated utilizing inflows of herbicide in solution with and without added sediment. The filter strips effectively trapped sediments reducing levels by over 70%, and reduced atrazine levels in solution by up to 59% (Mickelson & Baker, 1993).

Reduction of volume of irrigation following pesticide application would appear to be an effective tool in reducing pesticide losses, also. Pulsed or cycled irrigation is defined as a sequence of timed cycles composed of an irrigation phase and a resting phase (Karmeli & Peri, 1974). Smaller volumes of irrigation are applied at more frequent intervals reducing run-off amount and conserving water resources. Cycled irrigation reduced NH_4-N losses and reduced effluent volume in container plants (Tyler *et al.*, 1996).

The objective of our studies was to determine if vegetated waterways alone and in combination with pulsed irrigation would reduce the amount of pesticides lost in run-off water generated during containerized plant production.

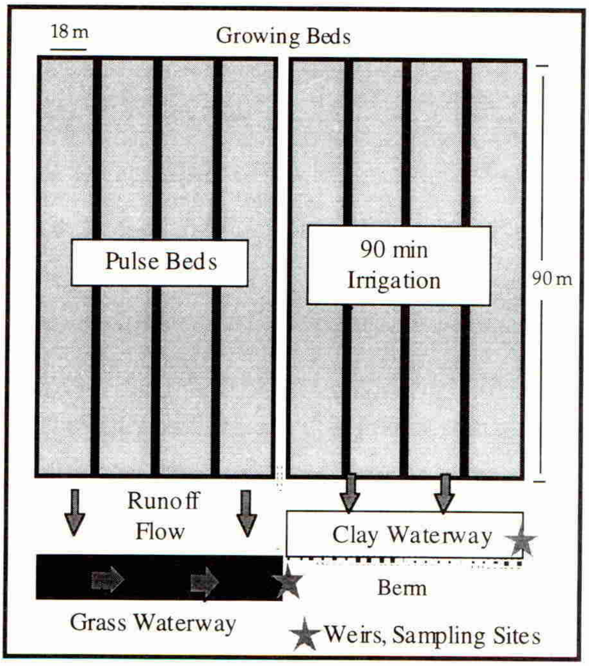
MATERIALS AND METHODS

Research was conducted at a wholesale container plant nursery in the north-western region of South Carolina. The nursery has a large (2 ha) growing area which is isolated from the remainder of the operation and which slopes uniformly and unidirectionally so that run-off waters may be easily channelled. The site contains eight growing beds each 18 m by 90 m divided by gravel roadways. Each growing bed was irrigated by 18 overhead rotary impact sprinklers, and the production surface was a semi-permeable polypropylene landscape fabric over a layer of black plastic with compacted soil underneath. Irrigation rates averaged 0.8 cm/h. A hybrid Bermuda grass *(Cynodon dactylon x C. transvaalensis)* waterway (1.8 m x 90 m) on a 5% slope was installed at the downslope of four of the growing beds in the summer of 1994. Run-off from the other four beds was directed into the existing clay and gravel roadway (1.8 m x 90 m) defined through the placement of berms. Weirs (90_) were placed at the termination of both waterways to allow determination of run-off volumes and for sample collection (Figure 1).

In the first study, isoxaben (1 kg a.i./ha), plus trifluralin (4 kg a.i./ha) as the granular formulation 'Snapshot TG', were broadcast applied with hand-held spreaders. An irrigation event of 2 h duration immediately followed the applications. Run-off samples were collected at 0 (defined as head of run-off at weir = 2.54 cm), 20, 40, 60, 80, 100 and 120 minutes after inception of run-off from each waterway. Samples were collected after two pesticide applications during the summer of 1995, on the day of application, and 1, 2, 4 and 8 days after application.

In the second study, isoxaben plus trifluralin were applied as above. The section of the growing area in which run-off was directed into the clay/gravel waterway was immediately irrigated for 1.5 hours; the section bordered by the grassed waterway was irrigated by three 30 minute pulse cycles, with a 90 minute interval between cycles. Run-off samples were collected through 8 days after application as in the first study. Water samples were taken at the beginning of run-off and at 20, 40, 60, 80 and 100 minutes of run-off flow from the clay/gravel waterway. Samples from the grassed waterway were taken at the beginning of run-off, and after 20 minutes of flow for each of the pulsed cycles. The herbicide applications were made in late summer, 1996.

Figure 1. Site layout of nursery research area.



Extraction and analysis

Extraction and analysis methods were as described by Briggs *et al.*, 1996. Percent recoveries were 121% for isoxaben and 78% for trifluralin. Limits of detection were <50 ppb.

RESULTS

Run-off characteristics

In the first study, irrigation events at a rate of 1892 litres/min delivered ≈ 227,000 litres of water. Peak flows were noted between 70 and 120 minutes after run-off began for each waterway. The flow rate from the grass waterway was higher than from the clay/gravel waterway, but was of shorter duration. Of the total volume of water applied as irrigation to both treatments, 34% was recovered from the clay/gravel waterway, and 34% from the grass waterway. Therefore, irrigation efficiency (volume of water applied minus volume of water recovered) was at most 32%.

Run-off volume from the pulsed treatment in the second study averaged 29,900 litres, approximately 60% of the amount of water applied as irrigation. Volumes were lowest from the first pulse cycle (6835 litres), highest for the intermediate cycle (11,733 litres) and slightly lower in the last cycle (11250 litres), perhaps because of greater evaporation potential. Run-off volumes from the continuous irrigation treatment averaged 36,500 litres, 71% of applied amounts. Total volume of run-off water from the pulsed treatment was 18% less than for the continuous irrigation treatment.

Isoxaben concentrations

In 1995, isoxaben was detected throughout 4 days after application in both waterways. The highest concentrations of 3.26 and 1.89 µg/ml were noted within the first 20 minutes of run-off on the day of application for the clay/gravel and grass treatments, respectively. The greatest daily concentrations were consistently noted within the first 20 to 40 minutes of run-off, with values decreasing through the remainder of the run-off duration. Detected concentrations were lower for each subsequent sampling day for both waterways, and were below limits of detection at 8 DAA.

The concentration of isoxaben in the second study was higher from the pulsed/grassed waterway treatment in early samples (when run-off volumes were less) on the day of application, but lower for the last sample of the second pulse cycle and for both samples of the third cycle. The highest concentration detected was 1.2 µg/ml from the first pulse sample on the day of application. Concentrations of isoxaben were consistently reduced on other sampling days by the pulsed/grass waterway treatment. Isoxaben was detected through 8 days after application in all run-off samples with amounts decreasing on each subsequent sampling days and approaching the limit of detection by the end of the study.

Trifluralin concentrations

Trifluralin was only detected from the clay/gravel waterway on the day of application during the first 60 minutes of run-off, in 1995. The highest concentration was 0.25 µg/ml at 20 minutes of run-off. No detectable amounts were noted in the effluent from the vegetated waterway. In the second study, trifluralin was detected on the day of application in run-off samples through 80 minutes from the continuous irrigation treatment and in only the initial pulsed sample. The greatest concentration detected was < 0.06 µg/ml. Concentrations of trifluralin were not reduced by the grassed waterway or the combined effect of grassed waterway and pulsed irrigation.

Trifluralin movement in run-off water is well researched. Highest concentrations reported were 0.014 and 0.035 µg/ml (Rohde *et al.*, 1980; Brown *et al.*, 1995). The higher pesticide concentrations noted in this study are probably a result of the presence of the impermeable ground cover, and the large volume of irrigation water applied immediately following herbicide application.

Isoxaben quantities

Total amounts of herbicides were calculated by multiplying concentration for a specific sampling period by run-off volume. The total amount of isoxaben lost from the waterways in 1995 was 121 and 122 g for the clay/gravel and grass treatments, respectively, or 23% of the total applied (Table 1). On the day of application, a difference was found among the treatments. Amounts detected were 16% lower from the grass treatment. Only on the day of application did amounts from the clay/gravel waterway exceed that detected in the grass treatment. The trend is of an initial reduction of pesticide load by the grass waterway followed by either a release of trapped material, or an inability to remediate further amounts.

Total isoxaben amounts which moved in run-off water were reduced 30% by the pulse/grassed treatment in 1996 (Table 1). The greatest reduction was on the day of application when isoxaben amounts from the pulsed/grassed treatment were 66% of the amount recovered from the continuous irrigation treatment.

The total amount of isoxaben detected in run-off water in 1996 represented 9% of the applied amount from the clay/gravel treatment. Wilson *et al.* (1996), detected 11% of applied isoxaben as transported in run-off water within five days of application. Isoxaben losses in run-off water were 23% of total applied in 1995 in which the volume of irrigation following herbicide application was 50% greater than in 1996.

Isoxaben has a low water solubility (1 to 2 mg/litre), but is a moderately polar pesticide, and will move in run-off if large amounts of water are provided. Dissipation of isoxaben is, additionally, a function of photolysis and microbial degradation. Wilson *et al.*, 1996, attributed losses of 14% of the total isoxaben applied to breakdown from natural light conditions. Mamouni *et al.*, 1992, reported 50% disappearance of isoxaben in 14 days in water under natural conditions. Volatilization and adsorption to groundcover material may have been additional fates of this herbicide.

Table 1. Amounts (g) of isoxaben recovered in run-off water from treatments on day of application (DOA), 1, 2, 4 and 8 days after application (DAA), and total, for the 1995 and 1996 studies.

	1995			1996		
Sample day	Clay/ gravel g	Grass g	LSD (*P*=0.05)	Clay/ gravel g	Pulsed/ Grass g	LSD (*P*=0.05)
DOA	68	57	9.0	19	12	5.9
1 DAA	27	32	10.0	10	7	13.7
2 DAA	21	25	5.8	10	7	5.5
4 DAA	4	7	6.3	4	3	2.9
8 DAA	ND[1]	ND	---	2	2	4.5
Total	121	122	28.6	45	32	9.8

[1] None detected.

Trifluralin quantities

Minimal amounts of trifluralin were detected, with <0.01% of the total amount applied recouped from any treatment in either study. The herbicide was detected in measurable amounts on the DOA only, with transport by run-off water minimal. Trifluralin is relatively insoluble in water (<1 mg/litre), and has a high vapor pressure (13.7 mPa at 25C). Losses from volatilization of surface residues are reported to be 100% in 48 h (Spencer & Cliath, 1974). The herbicide is also subject to photolytic breakdown, and has a strong affinity for soil adsorption, with residues of 10 - 15% detected 6 to 12 months after a soil incorporated application (Probst *et al.*, 1967). Adsorption to groundcover products may also be a fate of this herbicide, though residues were not detected as being released over time. As climatic conditions were conducive to high rates of volatility throughout these studies, minimal residues of the compounds may be expected.

SUMMARY

The major objective of these studies was to investigate the potential of easily implemented management practices to reduce herbicide loads in run-off water. Losses of isoxaben on the DOA were 16% lower from the grass waterway as compared to the clay/waterway channel in the 1995 study. Cumulative losses, however, were similar because detected amounts on subsequent days were slightly higher from the grass treatment. Hayes & Dillaha, 1992, stress the importance of minimal run-off flow velocities in order for vegetated filter strips to be effective remediators. Large flow volumes on succeeding days may have prevented filtration into the grass, or the waterway may have reached remediation capacity.

The combination of grassed waterways and pulsed irrigation appears to be an effective means of reducing pesticide movement in run-off water. When grass waterways are combined with a pulsed irrigation regime total losses of isoxaben were mitigated significantly. Vegetated waterways and pulsed irrigation appear to be effective tools for reducing pesticide levels in run-off water.

REFERENCES

Briggs, J A; Whitwell, T; Riley, M B (1996) Movement of chlorpyrifos and thiophanate-methyl in run-off water from a container nursery. *Proceedings Southern Nurserymen's Association Research Conference*. **41**, 50-52.

Brown, C D; Hodgkinson, R A; Rose, D A; Syers, J K; Wilcockson, S J (1995) Movement of pesticides to surface waters from a heavy clay soil. *Pesticide Science*. **43**, 131-140.

Dillaha, T A III; Sherrard, J H; Lee, D (1989) Long-term effectiveness of vegetative filter strips. *Water and Environmental Technology*. **1**, 418-421.

Gaynor, J D; MacTavish, D C; Findlay, W I (1995) Atrazine and metalachlor loss in surface and subsurface run-off from three tillage treatments in corn. *Journal of Environmental Quality*. **24**, 246-256.

Hayes, J C; Dillaha, T A (1992) Vegetative filter strips: 1. site suitability and procedures. Paper No. 92-2102. American Society Agricultural Engineers. St. Joseph, Michigan.

Karmeli, D; Peri, G (1974) Basic principles of pulse irrigation. *Journal of Irrigation and Drainage Division*. **100**, 309-319

Keese, R J; Camper, N D; Whitwell, T; Riley, M B; Wilson, P C (1994) Herbicide run-off from ornamental container nurseries. *Journal of Environmental Quality*. **23**, 320-324.

Mamouni, A; Schmitt, P; Mansour, M; Schiavon, M (1992) Abiotic degradation pathways of isoxaben in the environment. *Pesticide Science*. **35**, 13-20.

Mickelson, S ; Baker, J L (1993) Buffer strips for controlling herbicide run-off losses. Paper No. 93-2084. American Society of Agricultural Engineers. St. Joseph, Michigan.

Probst, G W; Golab, T; Herberg, R J; Holzer, F J; Parka, S J; Van der Schans, C; Tepe, J B (1967) Fate of trifluralin in soils and plants. *Journal of Agriculture and Food Chemistry*. **15**, 592-599.

Riley, M B; Keese, R J; Camper, N D; Whitwell, T; Wilson, P C (1994) Pendimethalin and oxyfluorfen residues in pond water and sediment from container plant nurseries. *Weed Technology*. **8**, 299-303.

Rohde, W A; Asmussen, L E; Hauser, E W; Wauchope, R D; Allison, H D (1980) Trifluralin movement in run-off from a small agricultural watershed. *Journal of Environmental Quality*. **9**, 37-42.

Schreiber, J D; Smith, S Jr.; Cullum, R F (1993) Pesticides and nutrients in southern US shallow ground water and run-off. *Water Science Technology*. **28**, 583-588.

Shaw, D R; Smith, C A; Hairston, J E (1992) Impact of rainfall and tillage systems on off-site herbicide movement. *Communications in Soil Science and Plant Analysis*. **23**, 1843-1858.

Spencer, W F; Cliath, M M (1974) Factors affecting vapor loss of trifluralin from soil. *Journal of Agriculture and Food Chemistry*. **22**, 987-991.

Tyler, H; Warren, S; Bilderback, T (1996) Cyclic irrigation increases irrigation application efficiency and decreases ammonium losses. *Journal of Environmental Horticulture*. **14**, 194-198.

Wilson, P C; Whitwell, T; Riley, M B (1996) Detection and dissipation of isoxaben and trifluralin in containerized plant nursery run-off water. *Weed Science*. **44**, 683-688.

APPLICATION OF HERBICIDES IMPREGNATED ONTO PLASTIC FILM IN EARLY VEGETABLES AND MAIZE

S R RUNHAM, S J TOWN, J C FITZPATRICK
ADAS Horticulture, Arthur Rickwood Research Centre, Mepal, Ely, Cambs, CB6 2BA, UK
e-mail Sally_Runham@adas.co.uk

ABSTRACT

Contact and residual herbicides were applied to carrots, potatoes and maize by impregnation onto plastic film. This technique is a form of precision farming, specific to crops for which plastic film is viable economically. The technique was tested for the first time under semi-commercial conditions in 1996. Perforated polythene covers were impregnated with linuron and placed over drilled carrots on a sandy loam soil in March 1996. Perforated polythene film covers were impregnated with either metribuzin or linuron and placed over pre-planted ridges of potatoes on a sandy loam soil in March 1996. For the evaluation on maize, non-perforated plastic film was treated with atrazine and laid onto a silt soil in June 1996. The maize seeds were sown by hand through the mulch at intervals and the seedlings found their way through the film. The technique gave effective weed control, which was similar to the standard sprayed system, where linuron was used on both carrots and potatoes, where atrazine was used on maize but not where metribuzin was used on potatoes.

INTRODUCTION

Plastic film covers provide a favourable microclimate which can advance crop maturity and/or increase yield (Eggers, 1975; Henriksen, 1985; Benoit & Ceustermans, 1990; Guttormsen, 1990; Runham & Town, 1993). The warmer soil and air temperatures beneath the film also encourage earlier germination of weeds (Bond & Birch, 1989; Bond & Walker, 1989). Under crop covers, weed control is difficult and may necessitate removal of the film cover to allow hoeing and herbicide application.

Some expensive non-woven covers allow uniform penetration of herbicides if applied in high rates of water (Davies & Hembry, 1994). Where less expensive polythene covers are used, residual herbicides may be applied prior to laying the film but contact herbicides cannot usually be applied through polythene. A new technique, whereby a herbicide was impregnated onto plastic film, proved effective in field pilot trials in the UK in 1995 (Runham, 1996a). The crops tested in 1995 were calabrese and lettuce, established in late summer on silt and peat soils. The technique was evaluated further in 1996 on potatoes, carrots and maize, established in spring and summer on sand and silt soils.

MATERIALS AND METHODS

Trial A-Early carrots in 1996

Carrots, cv. Primo, were drilled on 8 March 1996 into a sandy loam soil on a commercial holding. The plots comprised four rows of carrots across a 1.8 m bed which was covered with plastic film 2 m wide. All herbicide treatments, as a spray ('Linuron Flowable', 450 g/litre, PBI) and in plastic film, were applied on 11 March. Each plot was 7 m long (12.6 m^2). The crop was harvested when mature on 28 July 1996 when a 2 m length of each of the middle two rows was lifted.

A range of weed control treatments was applied as follows:

(i) Hand-weeded, no herbicide, covered with plastic film (200 holes/m^2),
(ii) Standard herbicide programme, sprayed with linuron at 585 g a.i./ha, covered with 200 holes/m^2 film,
(iii) Herbicide-impregnated plastic film (200 holes/m^2) with linuron at 585 g a.i./ha,
(iv) Herbicide-impregnated plastic film (200 holes/m^2) with linuron at 293g a.i./ha,
(v) Herbicide-impregnated plastic film with linuron at 585 g a.i./ha with non-perforated film, progressively ventilated (by hand) from 10, to 200, and to 400 holes/m^2 on 11 March, 27 March and 23 April respectively,
(vi) Herbicide-impregnated plastic film with linuron at 293 g a.i./ha with progressively-ventilated (as for (v) above) plastic film.

Trial B-Early potatoes in 1996

A crop of potatoes, cv. Maris Bard, was planted on 4 March 1996 with two rows 76 cm apart per plot and 10 m in length (15.2 m^2 in total). The sprays and plastic covers were applied on 6 March. The plastic covers were removed on 1 May and the trial was hand-weeded. Non-woven crop covers were applied to protect the trial from frost until harvest on 11 June 1996, when an 8 m length of each ridge was lifted and assessed.

The weed control treatments were as follows:

(i) Hand-weeded, no herbicide, covered with plastic film (200 holes/m^2),
(ii) Metribuzin ('Sencorex WG', 700 g/kg, Bayer) at 700 g a.i./ha sprayed, covered with plastic film (200 holes/m^2),
(iii) Linuron (as above) at 585 g a.i./ha sprayed, covered with plastic film (200 holes/m^2),
(iv) Herbicide-impregnated film (200 holes/m^2), with metribuzin (as above) at 700 g a.i./ha,
(v) Herbicide-impregnated film (no holes) with metribuzin (as above) at 700 g a.i./ha,
(vi) Herbicide-impregnated film (200 holes/m^2) with linuron (as above) at 585 g a.i./ha.

Trial C-Maize in 1996

A crop of maize, cv. Melody, was sown by hand through non-perforated plastic film on a silt soil on 4 June 1996. The trial was harvested on 4 October 1996 when 24 plants per plot were assessed.

The weed control and plastic film treatments were as follows:

(i) Crop hand-weeded, not mulched with plastic film,
(ii) Crop hand-weeded, mulched with plastic film,
(iii) Crop sprayed with atrazine ('Gesaprim 500SC', 500g/litre, Ciba Agric) at 1.5 kg a.i./ha, not mulched,
(iv) Crop sprayed with atrazine (as above) and mulched with plastic film,
(v) Crop mulched with herbicide-impregnated using atrazine (as above) at 1.5 kg a.i./ha, mulched with plastic film.

The sprayed herbicides were applied in 250 litres /ha of water using an Oxford Precision sprayer with F11002 nozzles (F11003 for carrots) and operated at 200 kPa pressure to give fine spray quality. All trial designs were randomized blocks with three replicates (four for the carrot trial). The population of crop plants, crop vigour, weed vigour and population and weed species were recorded on two occasions for all crops. The fresh yield in size grades was recorded at harvest. The oven dry weight of maize plants and cobs was recorded.

RESULTS

Trial A-Early carrots

Linuron, applied at 585 g a.i./ha, impregnated onto plastic film (200 holes/m^2), gave similar good control of weeds to the sprayed treatment initially but, better weed control than the sprayed treatment at the time of cover removal on 22 May 1996 (Table 1). The main weeds were *Bilderdykia convolvulus, Urtica urens* and *Chenopodium album.* Linuron, impregnated at 293g a.i./ha, half the normal rate onto the film, gave poor weed control when compared with the higher rate of linuron either sprayed or impregnated. None of the treatments affected carrot population. The sprayed and herbicide-impregnated treatments of linuron at 585 g a.i./ha gave similar total yields, both higher ($P<0.05$) than the untreated and the lower rate of herbicide-impregnation. Both weed control and yield were reduced ($P<0.05$) under progressively ventilated impregnated film.

Trial B-Early potatoes

Linuron, applied at 585 g a.i./ha impregnated onto plastic film (200 holes/m^2), gave similar weed control to the sprayed control (Table 2). Metribuzin, applied impregnated onto the plastic, gave poorer weed control than the sprayed control. The main weeds were *Urtica urens* and *Polygonum persicaria.* All treatments gave similar rates of crop emergence. Crop vigour on 1 May (not shown) reflected the degree of weed control achieved by that date, with high vigour for the sprayed application of metribuzin and linuron and for the impregnated linuron. These three treatments gave higher ($P<0.05$) yields compared with the other treatments where the weed control was poor.

Table 1. Effect of herbicide-impregnated plastic film on carrot and weed populations, weed cover and total yield of carrots (transformed data in parentheses).

Weed control and plastic film treatment	Carrot plants/m^2 DAD*		Weed plants/m^2 DAD*		Weed cover % DAD*		Yield (t/ha) DAD*
	33	74	33	74	74		142
(i)Hand-weeded, 200 holes/m^2	79	91	125	207	89	(70)	25.6
(ii)Sprayed 585 g linuron /ha, 200 hole/m^2 film	101	108	77	132	55	(48)	40.9
(iii)Linuron 585 g/ha -impregnated film (200 holes/m^2)	91	106	64	48	18	(24)	43.7
(iv)Linuron 293 g/ha -impregnated film (200 holes/m^2)	97	104	93	164	68	(55)	34.0
(v)Linuron 585 g/ha -impregnated film, (10,200,400 holes/m^2)	101	108	96	171	60	(51)	38.6
(vi)Linuron 293 g/ha -impregnated film, (10,200,400 holes/m^2)	99	107	126	191	76	(63)	33.9
S.E. (15 d.f.)	5.8	6.4	16.9	26.9	6.3	(4.2)	2.67
L.S.D.(5%)	N.S.	N.S.	N.S.	81.0		(12.8)	8.03

*DAD= days after drilling

Table 2. Effect of herbicide-impregnated film on potato population and yield and on weed population and cover.

Weed control and plastic film treatment	Potato hills#/m² DAP*		Weed plants/m² DAP*		Weed cover % DAP*	Crop total yield (t/ha) DAP*
	37	58	38	58	58	99
(i)Untreated, 200 holes/m²	2.7	38.0	388	457	98	4.0
(ii)Metribuzin sprayed at 700 g a.i./ha, 200 holes/m² film	5.0	39.0	96	78	5	8.4
(iii)Linuron sprayed at 585 g a.i./ha, 200 holes/m² film	9.7	40.7	118	184	13	8.0
(iv)Metribuzin impregnated at 700 g a.i./ha onto 200 holes /m² film	7.0	36.3	388	449	82	4.2
(v)Metribuzin impregnated at 700 g a.i./ha onto plastic with no holes	6.3	32.3	389	401	90	4.6
(vi)Linuron impregnated at 585 g a.i./ha onto 200 holes/m² film	9.7	35.7	169	190	10	8.0
S.E (22 d.f.)	3.87	4.16	79.1	143.2	7.6	1.62
L.S.D. (5%)	N.S.	7.05	134.0	242.5	12.8	2.74

Groups of potato stems arising from a single tuber
*DAP=Days after planting

Trial C-Maize

The application of atrazine by impregnation onto the plastic film gave good control of weeds, similar to the sprayed application (Table 3). The main weeds were *Chenopodium album* and *Cirsium* spp. The use of plastic film advanced crop growth throughout the season until harvest on 4 October 1996, when the crop grown without mulch appeared to have caught up with the mulched maize plants and fresh yields for all treatments were similar. All plastic-mulched treatments had a higher ($P<0.05$) percentage of oven-dry weight than the non-mulched treatments.

Table 3. Effect of herbicide-impregnated plastic mulch on weed cover and on crop vigour and yield in maize (transformed data in parentheses).

Weed control and plastic film treatments	Weed Cover % DAD*		Crop vigour score* DAD*		Crop yield (t/ha) Whole plant	
	38	62	38	79	Fresh	Dry
(i)Crop hand-weeded, no herbicide, not mulched	28 (31)	0 (0)	3.3	5.5	57.9	12.7
(ii)Crop hand-weeded, no herbicide, mulched	8 (10)	5 (11)	7.0	7.0	63.8	15.7
(iii)Sprayed with atrazine, not mulched	2 (7)	1 (5)	3.5	5.8	59.1	13.1
(iv)Sprayed with atrazine, mulched	0 (0)	0 (0)	7.5	8.3	67.7	17.9
(v)Atrazine -impregnated film	0 (0)	0 (0)	6.0	8.5	66.0	16.1
S.E. (12 d.f.)	(4.8)	(2.3)	0.31	0.62	4.6	0.72
L.S.D. (5%)	(14.8)	(7.1)	0.95	1.92	N.S.	2.21

*DAD=days after drilling

DISCUSSION

Results from the experiments in 1996 indicated good weed suppression using herbicide-impregnated plastic film for the application of linuron on both potatoes and carrots and for the application of atrazine on maize. The weed suppression in carrots using linuron applied impregnated onto plastic film lasted longer than that of the sprayed control. There was no evidence (from single samples only) that the herbicide residues in the crop and soil at the time of cover removal were higher for the herbicide-impregnated technique than for the standard sprayed/ plastic film-covered crop, but it is likely that both will be higher than for a crop grown without plastic film (Bond & Walker 1989, Jensen *et al.*, 1985; Rouchaud *et al.*, 1988, Runham, 1996b). Metribuzin, applied impregnated onto plastic film, was not as effective as sprayed metribuzin in potatoes. The lack of efficacy was attributed either to slow release of the herbicide from the film, and subsequent poor residual weed control, or to the lack of contact between the herbicide on the film and the soil in the valley between the potato ridges. The use of lower rates of herbicide in carrots did not prove efficacious. There is scope to reduce the overall rate per hectare either by employing strip application of herbicide on the film in a range of arrangements due to the precise application of the herbicide by printing onto the film. The environmental implications of using herbicide-treated film depend upon the type of plastic used and, in turn, the disposal options for the material at the end of the season. For non-degradable film, arrangement for safe collection and disposal would form part of the registration process (Kate Hoskin and Dave Bench, Pesticide Safety Directorate, pers. comm.). Degradable types of plastic film would remain in or on the land at the end of use, and the effects of this practice on the rates of breakdown of herbicide residue would require investigation. The commercial future of this technique and subsequent pesticide registration is under review.

ACKNOWLEDGEMENTS

The authors acknowledge the assistance of the Ministry of Agriculture, Fisheries and Food, UK for funding a review of literature related to this work and for the initial funding for the trial on early carrots. The funding for the remaining trials by IncoMulches Ltd, under a Department of Trade and Industry SMART award, is also acknowledged. The assistance of Bayer is acknowledged.

REFERENCES

Benoit, F; Ceustermans, N (1990) Effect of the removal of the two direct cover sheetings on the development of carrots. *Acta Horticulturae.* **3,** 267-274.

Bond, W; Birch, P J (1989) Weed control in carrots and salad onions under low-level polythene covers. *Brighton Crop Protection Conference- Weeds* 1989, 1021 -1026.

Bond, W; Walker, A (1989) Aspects of herbicide activity and persistence under low level polythene covers. *Annals of Applied Biology.* **114,** 133-140.

Davies, J S; Hembry, J K (1994) Weed control strategies under film crop covers. *Acta Horticulturae.* **371,** 283-287.

Eggers, H (1975) Untersuchungen zum klima unter verschiedenen Folienabdeckungen. Institute of Technical Gartenb. Landwirtschaft, Hanover 158 pp.

Guttormsen, G (1990) Effect of various types of floating plastic films on the temperature and vegetable yield. *Acta Horticulturae.* **267,** 37-44.

Henriksen, K (1985) Covering vegetable seed beds with plastic film. *Meddedelse, Statens Planteavlsforsog* 1985. 87 (1827): 4pp.

Jensen, K I N; Kimball, E R; Ricketson, C L (1985) Effect of perforated plastic row covers on residues of the herbicide DCPA in soil and broccoli. *Bulletin of Environmental Contamination and Toxicology.* **35** (6), 716-722.

Rochaud, J; Metsue, M; Himme, M Van; Gillet, J; Benoit, F; Ceustermans, N (1988) Biodegradation of chlorbromuron in the soil of rape celery (celeriac) crops made in greenhouses or in fields covered or not with plastic sheets. *Mededelingen van de Faculteit Landbouwwetenschappen, rijksuniversiteit Gent.* **53** (3b), 1455-1458.

Runham, S R; Town, S J (1993) Early performance of green celery cultivars under a double cover of plastic film. *Annals of Applied Biology.* **122,** *Supplement Tests of Agrochemicals and Cultivars.* **14,** 170-171.

Runham, S R (1996a) Herbicide application technique to crops grown with plastic film covers. *Second International Weed Control Congress.* Volume II, 925-930.

Runham S R (1996b) *The Mode of Action of Herbicides applied to crops grown under plastic film, including imprinting of the herbicide on the undersurface of the film.* A desk study for the Ministry of Agriculture, Fisheries and Food (MAFF). 22 pp. (Report not published, contact MAFF, Nobel House, 17, Smith Square, London, SW1P 3HX.

APPROACHES TO THE DETECTION OF INDIVIDUAL PLANTS IN HORTICULTURAL ROW CROPS AND THE IMPLICATIONS FOR PESTICIDE APPLICATION

P C H MILLER, T HAGUE, N D TILLETT, J A MARCHANT
Silsoe Research Institute, Wrest Park, Silsoe, Bedford, MK45 4HS, UK

ABSTRACT

The potential to modify the way in which pesticide treatments are applied to high value vegetable crops using automated field systems which detect row and plant positions is considerable. An experimental system has been developed in which images from a camera, mounted on the front of a vehicle, have been analysed to provide information used to guide the unit down the rows and from which the position of individual plants within the crop row can also be detected. Results from preliminary field trials in transplanted brassica crops have shown that the unit is capable of guidance to an accuracy of typically better than 20 mm when compared with a manual assessment of crop row positions. Used to direct treatments at identified crop targets, a standard deviation of 25 mm in treatment error from a vehicle travelling at a speed of 0.7 m/s was achieved and less than 10% of the ground area was treated with pesticide. The work to date has demonstrated the feasibility of automated crop treatment and further work is now proposed to quantify the benefits that this will give in defined crop/application conditions.

INTRODUCTION

Many chemical sprays used to treat low growing horticultural crops are conventionally applied from boom sprayers operating to treat the whole of the cropped area with a nominally uniform dose rate. Increasing environmental pressures have focused attention on the improved targeting of applications, such that biological efficacy can be maintained from using reduced quantities of pesticide. At the same time, pressures from the consumer, particularly via the major retail outlets, dictate that food crops should contain a minimum residue level.

A number of approaches to the improved targeting of pesticides applied to relatively widely spaced row crops have been successfully developed. Band spraying systems have been used to target the region between crop rows, for example when using a broad spectrum herbicide for weed control, or to target the region including the crop row when, for example, a selective herbicide might be used in conjunction with mechanical weed control between rows. The requirements for a more precise location of the spray head in relation to the target and improved control of the spray trajectory has often meant that the work rate of this type of equipment is lower than that of overall boom spraying.

Systems have also been developed for detecting the presence/absence of plants in a defined field condition. These have used a number of sensing methods including electrical conductivity, interrupted light beams and red/infra-red reflectance ratio mainly to detect the presence of a plant to be treated or retained without treatment in a selective thinning strategy. Some research and development has also been directed at the identification of crop rows from camera images, with a recognition that real images are likely to suffer from problems due, for example, to poor contrast between crop and soil and incomplete crop rows. A number of approaches to the analysis and interpretation of such images have been taken and these have been briefly reviewed by Brivot & Marchant (1996). Recent research as part of the project work described in this paper has aimed at using as much of the data and prior knowledge that is available in order to provide a robust method for finding the row structure in collected images.

The approach of identifying crop rows, crop and/or spray targets "on-line" is, in concept, an alternative to the map based control strategies used in patch spraying applications (Stafford & Miller, 1993, Miller, *et al.*, 1995) but with the same overall objectives. It is also likely that there will be important and useful commonalities between the two approaches. The use of an autonomous vehicle working in a row crop, sensing characteristics of the row structure and the crop provides the potential for the generation of maps that can be used to monitor crop development and pest/disease problems in a spatially variable manner. Perhaps most importantly, both approaches are capable of generating automatic and detailed records of the treatments applied to crops. This has important implications relating to traceability, crop production protocols and produce quality which are now key issues in relation to the production and marketing of many agricultural and horticultural commodities.

The next three sections of this paper summarise work by Hague, Tillett and Marchant (Hague & Tillett, 1996, Marchant, 1996, Marchant et al., 1997) in some detail so as to provide a background for discussion of the implications of this work.

THE EXPERIMENTAL VEHICLE

The vehicle used for the project work was based on a commercially manufactured tool carrier for use in horticultural applications, which was modified to enable automatic control. The two front wheels of the tool carrier were driven by a petrol engine via independent hydrostatic transmission units. The transmission ratios of these two units was adjusted by DC servomotors. Rotary encoders were fitted to monitor the forward travel of each of the driven front wheels with a resolution of 1792 counts per revolution. The vehicle was fitted with an accurate solid state compass capable of providing heading measurements to an accuracy of better than 1° and which were not prone to drift. To accurately obtain heading information in the horizontal plane, information relating to the roll and pitch angles of the vehicle was needed and these were obtained from two accelerometers mounted at right angles to each other directly over the centre of the axis of the driven wheels. A video camera which was sensitive in the near infra-red part of the spectrum was mounted centrally at the front of the vehicle looking forwards and down.

An on-board computer system consisted of a portable 486 PC with an interface to a transputer network. All control and sensing functions, including the image analysis, were carried out using the network of Inmos T800/T805 transputers. Control instructions to the vehicle were input via the portable computer. The speeds of the driven vehicle were maintained at the demanded values by the control algorithm. The sum of the two wheel speeds was determined by the required forward speed and the difference used to steer the vehicle. At the end of a row, the vehicle was programmed to complete a 180° turn and re-enter adjacent rows of crop.

The vehicle was also equipped with a marking device consisting of linear array of 27 solenoid valves at a 50 mm pitch mounted across the full width of the vehicle. Each solenoid valve was independently controlled by the computer system and was fitted with a jetting nozzle directed downward.

Experiments with the vehicle and to validate the approach to vehicle location and navigation have been conducted in a range of crop conditions including brassica, sugar beet and cereals grown in double rows 350 mm apart (Marchant, 1996).

VEHICLE LOCATION AND NAVIGATION

The movement of the vehicle follows one of two basic patterns: a path defined by the crop row and a path relating to a headland turn manoeuvre. Because the images obtained by the camera system on the front of the vehicle were required to distinguish, for example, between crop and weed, a relatively close up field of view was required. This meant that only a small part of the crop row was obtained in each image (Figure 1) and hence the information from which the row direction could be determined was limited. Typically the field of view was 2.0 m wide and 2.5 m down the crop row. A robust method of determining the row structure has been developed (Brivot & Marchant, 1996, Marchant, 1996) which initially uses a thresholding procedure to enhance the contrast between the crop, soil background, weeds, stones and other debris. A mathematical procedure is then used to identify the row structure within the captured image.

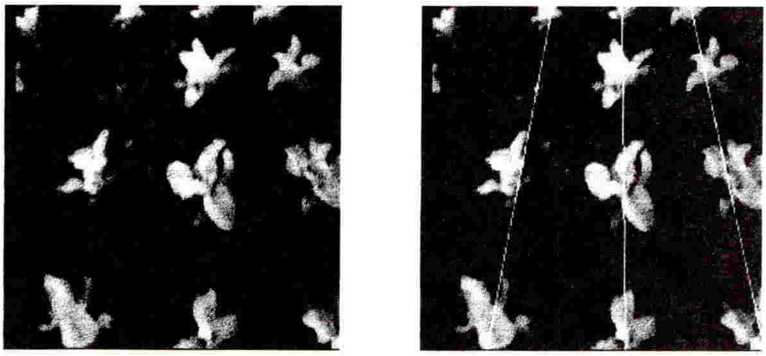


Figure 1. Images from a sequence containing cauliflower. Left, camera view seen in the near infra-red. Right, calculated row structure overlayed on the image.

Although the information obtained from the image analysis procedures was relatively robust and tolerant of disrupted crop rows with, for example, missing plants (Marchant *et al.*, 1997), the system may be required to work in conditions where the crop is difficult to distinguish because of a heavy weed infestation. Also, processing speed limitations meant that guidance control information was not available to the controller at the required frequency. For these reasons, information from the wheel speed sensors and accelerometers was used to provide position estimates during periods of dead reckoning navigation with no information from the image analysis, particularly at the headland. An arrangement of computer based filtering structures was used such that the estimates of position from the image analysis methods produced every 100 ms was supplemented by integrating information from the other sensors to give position estimates every 20 ms.

The accuracy of the row following control was assessed by using a stream of dye emitted from a nozzle mounted over the centre-line of the vehicle. The trace produced was compared with the true row positions determined from the mean lateral position of the three plants comprising the bed and differences measured manually. The results of this trial gave a standard deviation in the measured lateral offset of 20 mm and are reported in more detail by Marchant *et al.*, (1997).

The ability of the vehicle to follow a specified headland path was also accessed using similar experimental techniques. The vehicle was started part way down a bed of cauliflower, approximately 10 m from the headland. The end of the row was detected by the absence of plants in the row positions at forward distance which was within the supplied tolerance of row length. The specification of an approximate row length avoided premature turns occurring should a small patch of crop be missing. Having detected the headland automatically, a headland turn is initiated. The results in Figure 2 show a measured and commanded path during a typical headland turn, and indicate that the maximum error was approximately 60 mm such that the controller was required to make only a minor re-alignment correction as the vision system identified the next bed of cauliflower. Once aligned with the next bed, the vehicle then used the image analysis procedures described above to continue row following.

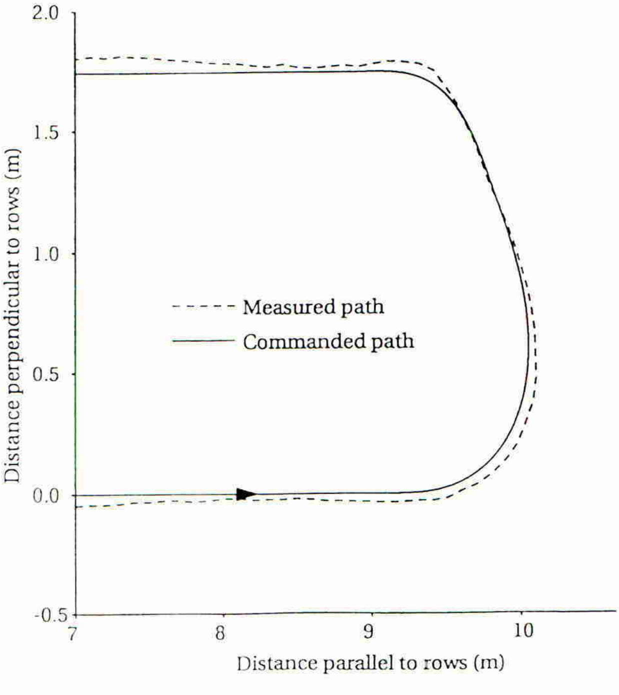


Figure 2. The measured and commanded vehicle paths during an automatic headland turn

Although detailed assessments of the reliability of the field navigation and headland turn routines have yet to be conducted, the experimental vehicle has operated successfully in a wide range of crop conditions including brassica crops at a range of growth stages and planted both manually and with a mechanical transplanter. In practice, the reliability of the approach is likely to be strongly linked to the state of the crop, the soil and the lighting conditions. This will have implications for the way in which reliability is assessed and also the way in which the approach is further developed.

SIMULATED CROP TREATMENT WITHIN THE ROW

The algorithm used to distinguish between plants, weeds and soil used in the identification of crop rows (Brivot & Marchant, 1966) has also been used as the basis for applying a simulated treatment to the crop. Plants detected within the region identified as the crop row were assumed to be crop and those outside neglected. The sequential images were used to create a local map as shown in Figure 3 and this was then used to control the array of single stream nozzles mounted beneath the vehicle. The images input to the mapper were perspective views and needed to be corrected as shown in Figure 3. Each image is overlaid on the previous image including a correction for motion of the vehicle. Figure 3 shows how an exaggerated vehicle motion was corrected making the rows straight on the map and independent of the vehicle motion. Because images were provided every 0.2 seconds, at normal operating speeds of up to 1.5 m/s, the images overlapped such that each area of the ground was effectively seen three or four times. These successive views were accumulated onto the map and the final classification into plant, weed or soil was made from the combined images. This added to the robustness of the crop plant detection and minimised effects due to the effects of shadows partly obscuring an image.

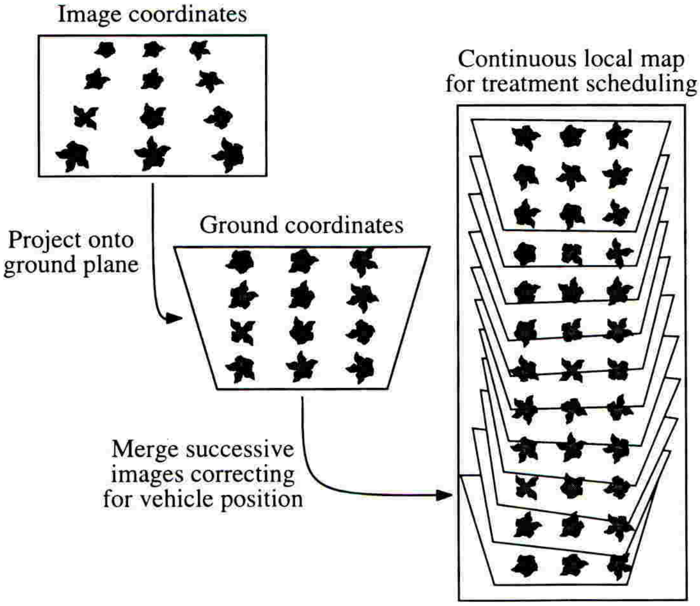


Figure 3. Merging segmented images onto the local map

The liquid stream jet nozzles were activated according to the map at 50 ms intervals such that, at a nominal forward speed of 1.0 m/s, the spatial resolution of the treatment was approximately 50 mm in both the lateral and along the direction of the crop row. The accuracy of treatment with the stream jet nozzles was assessed in a field trial in which a tracer dye was directed at crop plants. The unit travelled down crop rows at a speed of 0.7 m/s and the local map generated was stored in the computer. The location and state of each of the nozzles was recorded as they were actuated. At the end of a run, the treated area was photographed to record the positions of the dye output in relation to the crop plant positions.

The results from a typical run are shown in Figure 4. Figure 4(a) shows the local map with the areas classified as crop plants shown in black. The vehicles logged positions of where the stream jetting nozzles were turned on are shown in Figure 4(b) and Figure 4(c) shows a photograph of the treated area.

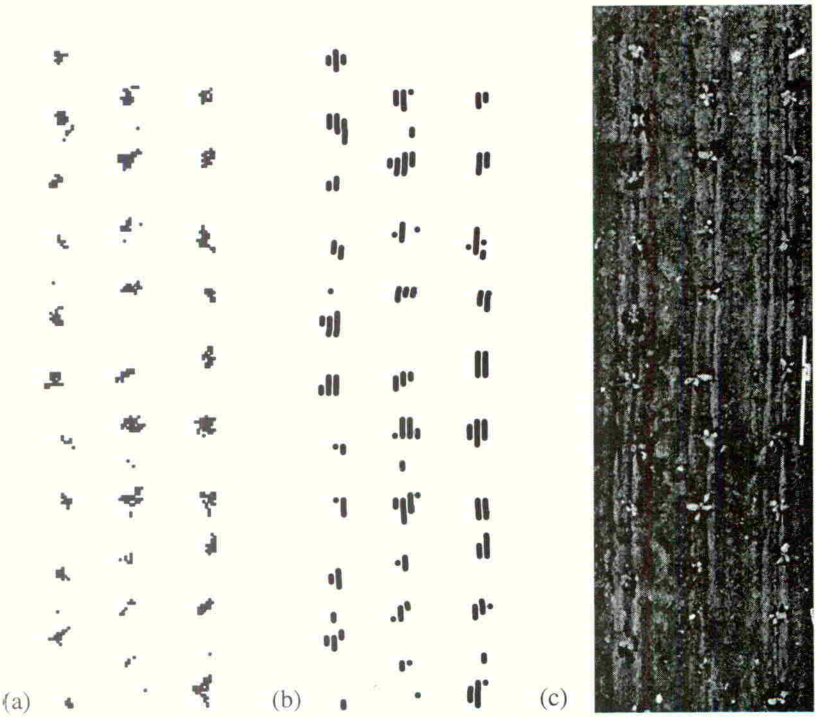


Figure 4: Results from field treatment trials: (a) local map generated on the vehicle; (b) treatments applied via activated stream nozzles;(c) photograph of the treated area

The results in Figure 4 show that all the plants were detected and treated although the lengths of the treated row did not always match that occupied by the plant. Some spurious spray operations resulted from the incorrect identification of the bright features in the image due for example, to stones, as plants. The centre positions of the plants and the corresponding positions of the treated area were measured and found to differ by a mean distance of 1 mm. This indicated a very small but consistent bias in the application of the treatment to the identified target. The standard deviation about this biased position in the direction along the row was 26 mm. In the lateral direction, the mean error was measured at 11 mm with a standard error of 20 mm.

The area covered with the output from the stream nozzles occupied only 8% of the total area and indicated the potential scope for reducing pesticide use by, for example, accurate targeting of the crop to be treated.

IMPLICATIONS OF THIS TECHNOLOGY FOR OPTIMISING PESTICIDE USE

Experiments with the vehicle have demonstrated the feasibility of systems based on automatic detection of the crop rows and detection of plants within the rows. The use of such systems to apply pesticides under typical field conditions has important implications concerning the pesticide formulations used, the quantities of pesticide required to achieve a given level of biological control and the appropriate methods of application. Conventional pesticides designed for use in overall application systems must balance the toxicity to non-target organisms with the requirements to produce an adequate biological response from material deposited on, for example, the plant target. Using an application system which places a much higher proportion of the total pesticide used onto the target area, may mean that products with a different toxicological profile can be approved for such a use. This argument is particularly relevant when, for example, a herbicide might be used for inter and intra row weed control and where the potential to minimise pesticide deposits on the crop will have direct implications for residue levels and harvest intervals.

The ability to improve the targeting of the pesticide application should also minimise the quantities of pesticides used to achieve a defined level of biological control. The potential for savings will depend on particular crop/weed/pest situations but results from experimental work targeting grass weed patches in cereal crops has indicated that savings in the order of 50% of herbicide use can be achieved (Stafford & Miller, 1993). For horticultural crops, quality requirements and the potential for harvesting problems means that high levels of weed control must be maintained. Results from the work reported here indicate that this could be achieved with substantially reduced pesticide use and associated financial and environmental benefits.

The treatment application system fitted to the experimental vehicle comprising the row of stream jet nozzles was selected for use in an evaluation programme relating to the detection and control aspect of the system performance. These would not be appropriate for the efficacious application of most pesticide treatments where droplet size and volume distribution at the target surface are important parameters influencing retention, up-take and the mode of pesticide action. Further work is now required to identify an appropriate configuration of an application which can enable the potential advantages of accurate targeting to be fully exploited while minimising system losses.

Most conventional pesticide application systems have been developed to apply a uniform volume distribution of a spray liquid at the target surface. With application systems that are able to identify detailed positions and sizes of spray targets, a different approach to the generation and transport of the spray is required. This needs to be able to match the delivery of spray to target position and dimensions, give some adjustment for dose rate and use physical characteristics of the spray that will give good surface retention, coverage and uptake. A research programme to examine possible application strategies and methods is currently being formulated.

Experiments with the vehicle to date have been conducted in good field conditions, on a level site and with relatively well established clean crops. There is a need for further research to develop and validate these approaches for operation in a wider range of conditions particularly associated with lighting conditions that can give long shadows. For a vehicle to operate completely autonomously, very high levels of reliability will be required including the possibility of using a secondary independent location system based for example on the Global Positioning System (GPS). The use of an absolute positioning system would provide direct links to the spatially variable application of pesticide treatments with further advantages of improved targeting. The methods of row and crop plant detection could also be used on a manually operated vehicle where the operator could oversee the performance of the unit and intervene in difficult operating conditions if needed.

CONCLUSIONS

Work to date has shown that the automatic application of pesticides to widely spaced row crops is technically feasible using a control system based on image analysis. The image analysis is able to identify crop rows and the positions of plants within the rows. When used with information from other sensing systems this can be used to navigate within the field and apply treatments selectively to programmed targets. Such an approach is particularly suited to the application of herbicides to horticultural crops and should enable reduced pesticide usage to be achieved while maintaining the highest possible produce quality standards. Further work is required to improve the reliability of the system and to develop application systems that can fully exploit the advantage of detecting spray target position and size.

REFERENCES

Brivot, R; Marchant J A (1996) Segmentation of plants and weeds for a precision crop protection robot using infra-red images. Proceedings of the Institution of Electrical Engineers. *Vision, Image and Signal Processing*, **143** (2), 118-124

Hague, T; Tillett, N D (1996) Navigation and control of an autonomous horticultural robot. *Mechatronics,* **6(2)**, 165-180

Marchant, J A (1996) Tracking of row structure in three crops using image analysis. *Computers and Electronics in Agriculture*, **15** (2), 161-179

Marchant, J A; Hague, T; Tillett, N D (1997) Row following accuracy of an autonomous vision guided agricultural vehicle. *Computers and Electronics in Agriculture*, **16** (2), 165-175

Miller, P C H; Stafford, J V S; Paice, M E R; Rew, L J (1995) The patch spraying of herbicides in arable crops. *Brighton Crop Protection Conference - Weeds*, **3**, 1077-1076

Stafford, J V; Miller, P C H (1993) Spatially selective application of herbicide to cereal crops. *Computers and Electronics in Agriculture*, **9**, 217-229.