Session 10

Weed Control in Major Crops

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THE IMPACT OF SULFONYLUREA HERBICIDES IN CEREAL CROPS

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ABSTRACT

Since 1982, 17 sulfonylurea active ingredients have been commercialized (or are in advanced development) for use in wheat, barley, rice and maize, while 6 others have been commercialized for use in other crops. These tools have been widely adopted with over 50 MM hectares of these cereal crops treated in 1994. The sulfonylurea share of the total herbicide market continues to grow. Growers have widely accepted this new technology because it meets their needs for products with wider application timing, a preference for postemergence applications, a choice in residual weed control, good crop safety and specific product related factors. These will be reviewed and related to general and compound-specific properties of these herbicides. The sulfonylurea herbicides have allowed a 50-100-fold reduction in application rate relative to older materials. These low rates have resulted in an estimated annual 100 million kg reduction in herbicide applications and a 2-3 billion kg reduction in chemical waste associated with agrichemical production. Adoption of sulfonylurea herbicides has contributed to alleviating societal concerns about agrichemical toxicity, effects on non-target organisms, and chemical residues in food. General issues sometimes associated with herbicide use are addressed specifically for the sulfonylurea herbicides.

INTRODUCTION

Two decades after their discovery (see Levitt, 1991), sulfonylurea herbicides continue to have widespread and increasing impact on world agriculture. Aside from providing multiple improved or unique utilities to growers around the world, many of the concerns about the use of agricultural chemicals are addressed by the properties of sulfonylurea herbicides. Use of sulfonylurea herbicides provides the yield increases associated with chemical weed control while reducing the chemical application to treated fields by 95-99% relative to higher use rate alternative products. A corresponding reduction in chemical manufacturing waste and packaging material is also realized when sulfonylurea herbicides are widely adopted. Further, the small amount of chemical used for weed control is itself essentially non-toxic, readily degraded by chemical and microbial processes in soil, and leaves no significant residues in the crop or environment. In addition, the biological activities of sulfonylurea herbicides are consistent with postemergence applications (allowing greater application flexibility and avoidance of prophylactic treatments) and are compatible with minimum or no-till agriculture.

Despite the well-established properties of the sulfonylurea herbicides, their commercial success has led to renewed scrutiny by some scientists, regulators, and environmental interest groups to insure that widespread use remains environmentally sound. In this paper, we describe the broad and practical impact that sulfonylurea herbicides have had on wheat, rice and maize agriculture and document market acceptance of this technology. We will review the toxicology and environmental fate properties of this "change technology" in the context of meeting society's requirements for an abundant food supply produced without attendant risk to people or the environment. We will also address several issues that are sometimes raised about these herbicides.

AGRONOMIC UTILITY : IMPACT ON SMALL GRAIN, RICE AND MAIZE GROWERS

Introduction of chlorsulfuron in 1982 in Australia and the United States began the commercialization of one of the most flexible and widely adaptable classes of herbicidal chemistry in agricultural history. To date, 23 distinct sulfonylurea active ingredients from seven manufacturers have been commercialized or are in advanced development for use in various crops including wheat, barley, oats, rice, maize, turf, soybeans, oilseed rape/canola, flax, sugarbeets, plantation crops, pastures, forestry, lowbush blueberries, potatoes, and tomatoes (see Brown and Cotterman, 1994). The biological activities of these herbicides have been adapted to the broadest possible agricultural conditions and systems throughout the world, ranging from Canadian dryland barley to temperate and tropical paddy rice to intensively managed wheat/ sugarbeet rotations in Europe. In 1994, it is estimated that more than 57 MM hectares were treated with sulfonylurea herbicides (DuPont, unpublished), and in our opinion, continued growth plus products in development will nearly double this area within 10 years.

Tables 1-3 summarize the application rates, dates of first sales, and key agronomic properties of the commercial and advanced candidate sulfonylurea active ingredients in wheat, barley, rice and maize.

Table 1: Sulfonylurea herbicides for wheat and barley

Active Ingredient/ Application Rate	First Sales	Key Utilities
Chlorsulfuron 9-25 g ai/ha	1982	Residual broad spectrum broadleaf and select grass weeds, esp. in low rainfall cropping systems
Metsulfuron Methyl 3-7.5 g ai/ha	1984	Moderate residual broad spectrum broadleaf weeds in low rainfall and intensive production
Thifensulfuron Methyl 15-20 g ai/ha	1987	Broad spectrum broadleaf weeds in intensive cropping systems
Tribenuron Methyl 9-18 g ai/ha	1987	Broad spectrum broadleaf weeds in low rainfall and extensively rotated systems
Triasulfuron 10-30 g ai/ha	1987	Residual broad spectrum broadleaf and select grass weeds, esp. in low rainfall cropping systems
Amidosulfuron 30-60 g ai/ha	1991	Select broadleaf weeds (esp. *Galium aparine*) in intensive cropping systems
DPX-KE459 10 g ai/ha	Pending	Select grass and broadleaf weeds in intensive cropping systems

Six sulfonylurea herbicides have been widely adopted in wheat and barley production, with over 39 MM hectares treated in 1994 (DuPont, unpublished). The flexibility of this chemical class is illustrated by wheat- and barley-selective actives which have been discovered for distinct agronomic needs including residual broadleaf weed control in the extensive dryland production areas of the U. S. central great plains, *Lolium rigidum* control in western Australian cereals, and short residual broadleaf weed control for areas of intensive crop production requiring rotation to broadleaf crops such as sugarbeets and oilseed rape throughout Western Europe. These products have also found special utility in double crop wheat/soybean/corn systems in the southern U. S. especially for *Allium vineale* control for which few alternatives exist. Sulfonylurea herbicides have provided excellent control of difficult and important weeds including *Stellaria media, Veronica* sp., *Fallopia convolvulus, P. aviculare, Galium aparine, Matricaria inodorum* and *Chenopodium album*. Some provided residual broadleaf activity not previously available at affordable prices, e.g. control of *Kochia scoparia* in the Great Plains of USA. DPX-KE459 (Table 1) is under development for control of *Alopecurus myosuroides* and *Apera spica-venti* at 10 g ai/ha, and will offer growers in Europe a new tool for these serious weeds when used at less than 0.5% the application rate of current products (Teaney *et al.* 1995).

Table 2: Sulfonylurea herbicides for rice

Active Ingredient/ Application Rate	First Sales	Key Utilities
Bensulfuron methyl 50-75 g ai/ha	1987	Residual broad spectrum annual and perennial broadleaf and sedge weeds, esp. in temperate rice
Pyrazosulfuron ethyl 20 g ai/ha	1990	Residual broad spectrum annual and perennial broadleaf and sedge weeds, esp. in temperate rice
Cinosulfuron 40-60 g ai/ha	1990	Broadleaf and select annual sedge weeds in temperate paddy rice
Imazosulfuron 100 g ai/ha	1993	Residual broad spectrum annual and perennial broadleaf and sedge weeds, esp. in temperate rice
Azimsulfuron (DPX-A8947) 6-9 g ai/ha	Pending	Residual broad spectrum annual and perennial broadleaf and sedge weeds. Grass activity at higher rate range.

The introduction of sulfonylurea herbicides in temperate paddy rice had major impact on grower practices in this market (see Table 2). Prior to the introduction of bensulfuron methyl in Japan, California, Italy, Spain and Portugal, few products existed that would provide adequate residual broadleaf and sedge weed control with a single application. The biological properties and low use rate of bensulfuron methyl helped further the development of the "One-shot" rice herbicide market in Japan, a market comprised of various mixtures of herbicides for control of *Echinochloa crus-galli* with bensulfuron methyl to provide truly broad spectrum annual and perennial weed control with a single application. Approximately 3 MM hectares of temperate rice were treated in 1994. The low application rates and favorable environmental properties of these broadleaf and sedge tools have also eased concerns about herbicide applications to water.

Table 3 lists three commercialized products and two advanced candidates for postemergence broadleaf and/or grass weed control in maize. Nicosulfuron and primisulfuron were the first herbicide tools (of any type) to provide effective postemergence grass weed control in maize. This new utility provided growers with a much needed option for control of the severely destructive weed *Sorghum halepense* as well as the control of other grass and select broadleaf weeds escaping preemergence treatments. By the latter half of the 1990's, a range of sulfonylurea herbicide products will be available to maize growers. These products will offer postemergence broad spectrum broadleaf and grass control and allow growers to adapt to rate reductions and restrictions on the use of preemergence products that are increasingly under regulatory pressure. The rapid adoption of rimsulfuron in Germany and Italy is partly due to severe restrictions on preemergence products and the discovery by growers that this postemergence technology is highly effective. Significant market growth for these sulfonylureas in maize is likely to be realized during the rest of this decade.

Table 3: Sulfonylurea herbicides for maize

Active Ingredient/ Application Rate	First Sales	Key Utilities
Nicosulfuron 35-70 g ai/ha	1990	Post broad spectrum grass and select broadleaf weeds
Primisulfuron 20-40 g ai/ha	1990	Post grass and select broadleaf weeds
Rimsulfuron 5-15 g ai/ha	1992	Post broad spectrum grass and broadleaf weeds
Halosulfuron methyl 18 - 35 g ai/ha 70 - 90 g ai/ha (pre)	1995	Pre/Post broadleaf weeds. Safener included for preemergence utility
Prosulfuron 20 - 40 g ai/ha	1995	Pre/Post broadleaf weeds

IMPACT ON SOCIETY'S EXPECTATIONS

The sulfonylurea herbicides have met society's expectations for agricultural benefit *and* environmental and human safety, and in some regards have set new standards for achieving this balance. As a class, sulfonylurea herbicides are exceptionally safe to handle and apply, leave virtually no residues in crops, are non-toxic to animal, microbial, and many algal and plant non-target organisms, degrade in soil by simultaneous biotic and abiotic processes, pose negligible threat to groundwater, and are non-volatile and minimally susceptible to drift. They also provide the yield and quality benefits of chemical weed control while reducing active ingredient application to fields by 95-99% relative to higher use rate products (with attendant reduction in manufacturing waste generation). Although a review of the full toxicity and environmental properties of the 17 sulfonylurea herbicides commercialized for cereal crops is beyond the scope of this paper, the following section summarizes some of these properties for select active ingredients. Additional reviews on these subjects are available (Beyer *et al*, 1987a; Blair and Martin, 1988; Brown, 1990; Brown and Kearney, 1991; Brown and Cotterman, 1994).

An important concern about agrichemicals is their safety to applicators, field workers and consumers. The sulfonylurea herbicides are exceptionally non-toxic in a broad battery of acute and chronic dietary, dermal, inhalation and eye tests in animals. Some of these results for metsulfuron methyl and thifensulfuron methyl are summarized in Table 4 and can represent the general results obtained with this herbicidal class. The results can be explained, in part, by the fact that the herbicidal target site of these compounds (acetolactate synthase) does not exist in animals, and the compounds are readily metabolized and excreted. In addition to the lack of toxicity in mammalian systems, the very low application rates of these herbicides (see Tables 1-3) and their ready metabolism in crops produces virtually zero residues in the harvested grain or straw of cereal crops (Beyer *et al*, 1987a; Brown *et al*, 1991; Brown and Cotterman, 1994).

Comparable acute and chronic toxicity testing has been conducted with a range of avian, aquatic, insect and other non-target organisms. Results typical for sulfonylurea herbicides are summarized for metsulfuron methyl and thifensulfuron methyl in Table 5. No toxicity towards birds, fish, aquatic and terrestrial arthropods, earthworms, or soil microbial processes was evident. The aquatic bryophyte *Lemna minor* exhibited sensitivity to

Table 4: Summary of mammalian toxicity results for metsulfuron methyl and thifensulfuron methyl.

Test System	Metsulfuron-Methyl	Thifensulfuron-Methyl
Acute	LD_{50}	LD_{50}
Oral	>5000 mg/kg bw[a,b]	>5000 mg/kg bw[a] >2600 mg/kg bw[c]
Dermal	>2000 mg/kg bw[c]	>2000 mg/kg bw[c]
Inhalation	>5.0 mg/L air[a]	>7.9 mg/L air[a]
Skin	Non-irritant[c]	Non-irritant[c]
Eye	Non-irritant[c]	Non-irritant[c]
Chronic	NOAEL	NOAEL
Oral (90 day)	1000 ppm[a,b,d]	100 ppm[a,b,d]
Oral (12 months)	>5000 ppm[d]	7500/750 (M/F)[d]
Oral (24 months)	500 ppm[a]	500 ppm[a]
Oncogenicity	Negative[a,b]	Negative[a,b]
Multigenerational Reproduction	500 ppm[a]	2500 ppm[a]
Teratogenicity	Negative[a,c]	Negative[a,c]

[a]rat [b]mouse [c]rabbit [d]dog

metsulfuron methyl and thifensulfuron methyl, consistent with the plant-specific activity of these herbicides. The effects observed below 0.64 µg/L (metsulfuron methyl) and 2 µg/L (thifensulfuron methyl) during the 14-day exposure period were partially-to-fully reversed during a 7-day recovery period. The results for these and other sulfonylurea herbicides indicate that they pose negligible toxicity risks to non-target organisms.

Besides toxicity, the other element of human and environmental risk assessment is the potential for exposure. Potential exposure to agrichemicals is related to use rate, compound physical properties (especially volatility), and fate in plants and the environment. In this regard sulfonylurea herbicides have several special advantages. The most obvious is their low application rates. Sulfonylurea herbicides are applied to wheat, rice and maize crops at rates of 3-100 g ai/ha (see Tables 1-3), which means that use of a sulfonylurea herbicide immediately reduces the quantity of active ingredient applied to treated fields by 95-99% relative to higher use rate alternative chemical products. The impact of this rate reduction can be dramatic at both the grower and global level. For example, a grower using a sulfonylurea herbicide in wheat could, in principle, apply that herbicide yearly for nearly a century before the total amount of chemical used would equal a single year's application of a higher use rate alternate product. Although it is quite debatable whether the higher use rate product is itself a problem even at 1-2 kg/ha, reduction of chemical application in the environment is generally desirable, and we know of no more dramatic step toward this end than the commercial acceptance of sulfonylurea herbicides. The global effects of this rate reduction can be estimated by recognizing that over 50 million hectares of wheat, rice and maize were treated with sulfonylurea herbicides in 1994 (DuPont, unpublished). Estimating an average application rate of 20 g ai/ha, this

Table 5: Summary of non-target organism toxicity results for metsulfuron methyl and thifensulfuron methyl.

Test System	Metsulfuron-Methyl	Thifensulfuron-Methyl
Avian	LD_{50}	LD_{50}
Mallard Oral Acute	>2510 mg/kg	>2510 mg/kg
Quail Dietary	>5620 ppm	>5620 ppm
Mallard Dietary	>5620 ppm	>5620 ppm
Aquatic Organisms	LC_{50}	LC_{50}
Rainbow Trout (96-hr)	>150 mg/L	>100 mg/L
(21-day)	>150 mg/L	>250 mg/L
Bluegill (96-hr)	>150 mg/L	>100 mg/L
Daphnia (48-hr)	>150 mg/L	470 mg/L
(21-day)	>150 mg/L	>340 mg/L
S. capricornutum[a] (120-hr) (EC_{50})	3.5 mg/L	15 mg/L
Lemna minor[b] (14-day) (EC_{50})	0.36 μg/L	1.3 μg/L
Other Non-Target		
Eisenia foetida (earthworm, 14-day) (LC_{50})	>1000 mg/kg soil	>2000 mg/kg soil
Honey bee (Contact, 48-hr) (LD_{50})	>25 mg/bee	>12.5 mg/bee
Soil Respiration (NOEC)	0.2 mg/kg soil	>0.53 mg/kg soil
Soil Ammonification and nitrification (NOEC)	0.2 mg/kg soil	>0.53 mg/kg soil

[a] *Selenastrum capricornutum* is an aquatic algae. Compounds were algistatic but not algicidal during the 120-hour test.

[b] Partial or complete frond regrowth occurred during a 7-day recovery period.

represents approximately 1 million kg of sulfonylurea active ingredients used in 1994 to accomplish the weed control that once required 100 million kg of higher use rate materials (at an average 2 kg/ha). The corresponding reduction in manufacturing process waste stream is dramatic but not often recognized. Waste streams of 10-100 kg waste per kg final active ingredient are not atypical of agricultural chemical production. If we assume an average of 30 kg waste/kg active ingredient, then approximately 3 *billion* kg of manufacturing waste have been eliminated annually through substitution of sulfonylurea herbicides for higher use rate products in wheat, rice and maize.

Sulfonylurea herbicides degrade in soil by a combination of chemical (i.e., abiotic) and biological processes (see Beyer *et al*, 1987a,b; Brown, 1990; Brown and Kearney, 1991). Table 6 summarizes average field and laboratory soil dissipation values for five sulfonylurea herbicides covering four distinct primary degradation mechanisms in soil. These primary degradation mechanisms account for the initial herbicidal inactivation of the respective active ingredient and include microbial metabolism and hydrolysis of the sulfonylurea bridge, accelerated bridge hydrolysis (afforded by the N-methyl modification

Table 6: Soil dissipation rates and primary degradation mechanisms of representative sulfonylurea herbicides

Active Ingredient	DT_{50}[a] (days)	Mechanisms
Metsulfuron methyl	14.7[b]	Microbial metabolism and pH-dependent bridge hydrolysis
Tribenuron methyl	2.1[c]	Accelerated pH-dependent bridge hydrolysis
Thifensulfuron methyl	2.2[d]	Microbially-catalyzed deesterification
Rimsulfuron	3-7[e]	*IPSO* Bridge Contraction
DPX-KE459	8-25[f]	*IPSO* Bridge Contraction

[a] Time required for the degradation of the first half of the applied compound.

[b] Average of DT_{50}'s from 10 field sites in the U. S. and Canada. DT_{50}'s ranged from 4-48 days.

[c] Average of DT_{50}'s from 3 U. S. field sites and 2 laboratory studies at 25°C

[d] Average of DT_{50}'s from 4 field sites in the U. S. and Canada. DT_{50}'s ranged from 0.42-7 days.

[e] Average of DT_{50}'s from 4 field sites in the U. S.

[f] Laboratory studies in 5 European soils at 20°C.

seen in tribenuron methyl), rapid deesterification of thifensulfuron methyl (Cambon and Bastide, 1992), and *IPSO* bridge contraction of rimsulfuron and DPX-KE459, where the urea nitrogen proximal to the pyrimidine ring attacks the pyridine ring at the bridge carbon, eliminating most of the sulfonylurea bridge and inactivating the herbicide (Schneiders *et al*, 1993; Teaney *et al*, 1995). In each case, the degradation products are non-herbicidal and non-toxic. As seen in Table 6, typical dissipation DT_{50}'s range from 2-15 days, refuting a misconception that sulfonylurea herbicides are persistent. In fact, from an environmental fate perspective, none of the sulfonylurea herbicides can credibly be labeled as persistent since each is shown to degrade by 90-100% within a single season under on-label usage. The impression that sulfonylurea herbicides are generally persistent arose from the fact that some products provide valuable residual activity against specific weeds in some geographies and require correspondingly extended recropping intervals for especially sensitive rotational crops. The reality is that a review of approved product labels reveals that only a few of the sulfonylurea products listed in Tables 1-3 have residual biological activity long enough to warrant recropping intervals longer than 1 growing season for relatively sensitive rotational crops, and these relatively longer residual products are labeled for agronomic system where such intervals are acceptable (such as wheat/fallow systems).

Chemical volatility is an important property affecting potential exposure to agrichemicals. The sulfonylurea herbicides are non-volatile, with vapor pressures ranging from $<<10^{-7}$-10^{-16} mm Hg (see Table 7). Several incorrect vapor pressure values were published during the early-to-mid 1980's. Some of these values persist in public literature and databases which has led to concern about volatilization. In fact, the extremely low vapor pressures of these herbicides are documented in registration dossiers for individual compounds and have been published (Beyer *et al*, 1987a). These vapor pressures are at least 10^4-10^7 times below values considered to be potentially volatile. The non-volatility of the sulfonylurea herbicides insures that material will not be lost in the gaseous form during storage, mixing, and application or from treated soil and crops after application. Also, spray drift of agrichemicals is primarily a function of applicator practices, wind and weather conditions, and nozzle and pressure variables, and these factors are routinely addressed on product labels. In fact, sulfonylurea herbicides are no more susceptible to spray drift during application than other agrichemicals, and their low vapor pressure provides an additional measure of safety in this respect.

Table 7: Vapor pressures of selected sulfonylurea herbicides

Active Ingredient	Vapor Pressure @25°C (mm Hg)
Chlorsulfuron	2.3×10^{-11}
Metsulfuron methyl	2.5×10^{-12}
Sulfometuron methyl	5.4×10^{-16}
Thifensulfuron methyl	1.3×10^{-10}
Tribenuron methyl	4.0×10^{-10}
Chlorimuron ethyl	3.7×10^{-12}
Nicosulfuron	1.2×10^{-16}
Bensulfuron methyl	2.1×10^{-14}
Azimsulfuron	3.0×10^{-11}
DPX-KE459	1.0×10^{-11}
Rimsulfuron	$<1 \times 10^{-7}$
Triflusulfuron	6.7×10^{-9}
Ethametsulfuron methyl	5.8×10^{-15}

ADDRESSING THE ISSUES

New technologies are often met with resistance, concern and skepticism during their introduction and adoption. The low application rates of the sulfonylurea herbicides have caused some to react with the concern that this herbicide technology might be fundamentally different from conventional use-rate herbicides. Among the least informed responses has been that such active herbicides must be correspondingly more toxic to other organisms, a reaction thoroughly discredited by the facts. Other issues including persistence in soil and rotational cropping, environmental fate, and volatility have been briefly reviewed in this manuscript and elsewhere. Three additional issues are raised in the following section and the reader directed to existing literature on these subjects (see below). These include mobility in soil and groundwater implications, analytical detection in the environment, and development of resistant weeds.

Although the sulfonylurea herbicides degrade relatively rapidly in soil, the moderate-to-low soil sorption of some members of this class (i.e., K_{OC} = 50-300) has occasionally raised concerns about mobility in soil and potential for leaching to groundwater. Russell *et al* (1995) have used the Pesticide Root Zone Model (PRZM) to calculate predicted concentrations of chlorsulfuron, metsulfuron methyl and tribenuron methyl in shallow groundwater pumped from 2 meter wells, using sandy loam soil parameters and moderate net aquifer recharge rates. These authors then related these calculated shallow groundwater concentrations (less than 0.0001 ppb even under these vulnerable conditions) to the US EPA lifetime human Health Advisory Levels (HAL) and the estimated range of sensitive plant response to irrigation water. They found safety margins ranging from greater than 10,000-fold to greater than 100,000-fold. When one considers that groundwater is routinely drawn from depths well in excess of 2 meters, it is apparent that despite the relatively low K_{OC} values for some sulfonylurea herbicides the threat to groundwater from these herbicides is virtually zero.

Development of the sulfonylurea herbicides and other low use rate agrichemicals required a step-change in analytical approaches to detect and quantitate trace residues in water, soil, and crops at levels less than one-hundredth previous quantitation limits. Analytical chemists have responded with new tools and procedures including HPLC with eluent and column switching, specialized detectors, LC/MS, and hapten-specific enzyme-linked immunoassays. Also, special sample handling and laboratory practices necessary to prevent sub-ppb contamination have been developed and must be adopted before laboratories can be certified to reliably analyze such samples. Despite these very significant challenges, sophisticated methods have been developed for specific sulfonylurea herbicides that allow limits of quantitation in soil of 0.1 to 1 ppb, a concentration range below levels in the field that can cause yield or quality loss in sensitive crops (Barefoot *et al*, 1995). Continued development work will make these methods more routine as more analytical laboratories invest in the instrumentation and expertise necessary to accommodate these and future classes of low use rate agrichemicals.

Pest resistance to herbicides, fungicides and insecticides is a well-established phenomenon, and a variety of strategies for managing pesticide resistance have been successfully applied to maintain the utility of these tools (see Cotterman, 1995). Weeds resistant to specific sulfonylurea herbicides (and other ALS inhibitors) have been documented and product labels modified to recommend management strategies (see Saari *et al.*, 1994). Concern about this development should be tempered by the fact that weeds resistant to other key herbicide classes, including inhibitors of Photosystems I and II, acetyl CoA carboxylase, tubulin polymerization, other acetolactate synthase inhibitors, as well as 2,4D and other auxin analogs have been widely documented. Yet these herbicides remain extremely valuable to agriculture. The large majority of sulfonylurea-resistant weed cases are restricted to instances of long-term monoculture with minimal rotation of crops or alternate herbicide classes. Most cases involve resistance in a single or very limited number of species, with activity on the remaining weed spectrum being maintained. Resistance to sulfonylurea herbicides is proving to be similar to other herbicide classes, and implementation of recommended management practices will help maintain the value of these herbicides for the foreseeable future.

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THE CONTROL OF HERBICIDE-RESISTANT *ALOPECURUS MYOSUROIDES* (BLACKGRASS).

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ABSTRACT

Field and glasshouse studies have been conducted since 1990 to identify potential resistance management programmes. The rate of resistance development and the effectiveness of herbicide-based management programmes have been assessed in long term, repeat-treatment trials. On the basis of the results obtained and the types of resistance mechanism present, a management programme is proposed which utilises clodinafop-propargyl with agronomic and cultural measures.

INTRODUCTION

Black-grass (*Alopecurus myosuroides)* is a seed propagated annual grassweed which due to relatively short dormancy and a propensity to autumn germination, (Fryer & Makepeace, 1977) has been found to be mostly associated with winter cereal cropping (Elliott *et. al*, 1979). *A. myosuroides* is an intensively competitive weed with cereal crops where uncontrolled moderate populations have been found to reduce yield potential by up to 45%, (Moss, 1987b). Uncontrolled or inadequately controlled *A. myosuroides* populations, in addition to the direct effect on yield also cause a reduction in grain quality and may ultimately disrupt optimum crop rotations and reduce land values. During the past twenty years, *A. myosuroides* in cereals has been generally adequately controlled by chlorotoluron and isoproturon and more recently by the new, cereal-selective “fop” herbicides fenoxaprop-ethyl and clodinafop-propargyl, both requiring to be used with a safener.

Some ten years after the first introduction of the phenylurea herbicides, *A. myosuroides* biotypes resistant to chlorotoluron were identified (Moss & Clarke, 1985). In 1990 phenylurea resistance was present on 46 farms in 19 counties (Clarke & Moss, 1991), which by 1992 had risen to 71 farms in 22 counties, (Moss & Clarke 1992, Clarke, Blair & Moss 1994). Perhaps of greatest significance in this latter report was the detection of resistance to fenoxaprop-ethyl on 90 farms after just two years of usage. Most of the resistant populations were in fields where intensive winter cereal cropping and non-ploughing techniques have been practised combined with the frequent use of herbicides from the same chemical class (Moss & Cussans 1991).

The benefits of ploughing to reduce *A. myosuroides* populations are well established (Clarke & Moss 1989, Orson & Livingstone 1987), and Clarke & Moss (1991) have shown the benefits of cultural control measures in assisting in the control of resistant biotypes. Developing from these studies, the Weed Resistance Action Group (WRAG 1993, Moss & Clarke 1994) published guidelines for the management of resistant *A. myosuroides*. These guidelines recommend utilisation of cultural, agronomic and chemical methods for the prevention and management of herbicide resistance.

As UK grain prices are progressively reduced in the future towards world market levels, farmers will scrutinise ever more critically their fixed and variable costs. Agricultural chemicals remain one of the farmer's most cost effective options, it is in this context that this paper examines *A. myosuroides* resistance management based on the use of clodinafop-propargyl and utilising aspects of the WRAG Guidelines.

MATERIALS AND METHODS

Replicated field trials were of a randomised complete block design using 24sqm plots and three replicates. Applications were made using a Ciba precision plot sprayer with six Lurmark 02F110 nozzles calibrated to deliver 200 l/ha at 207 kPa. The Northampton resistance development trial and the long term trials were unreplicated with plot sizes of 1440 sqm and 600-2400 sqm respectively with the same treatment being re-applied to the same plots each year with a Frazier Agribuggy at 200 l/ha. Products were the commercially available formulations: clodinafop-propargyl (Topik 240EC), fenoxaprop-P-ethyl (Cheetah Super), fenoxaprop-ethyl (Cheetah R), trifluralin (Treflan), triallate (Avadex BW Granular), and isoproturon (Hytane 500SC). The additive employed was a 97% mineral oil (Actipron or Adder). Blackgrass control in field trials was assessed by visual evaluation compared to untreated plots (presented data) and supplemented by headcounts. Glasshouse testing of *Alopecurus myosuroides* was undertaken according to the methodology described by Clarke, Blair & Moss (1994) and Moss & Orson (1988).

RESULTS

Table 1 presents the results from one of a series of *A. myosuroides* trials established in the autumn of 1991. The final weed control results showed poor performance with both isoproturon and fenoxaprop-ethyl, 68 & 43% control respectively, and a less than expected degree of control by clodinafop-propargyl of 95%. Seed from this field was subsequently tested in the glasshouse and resistance to fenoxaprop-ethyl and phenylureas was confirmed. On the basis of these results, this field was considered suitable for conducting a long-term, repeat application study to investigate resistance development and the performance of resistance management treatments with *A. myosuroides* biotypes expressing both phenylurea and "fop" resistance. The results from the first three years of this study are presented in Table 2.

Table 1. Northants Replicated Field Trial Results - Season 1991-92

Compound	G.AI/Ha	% Control
Untreated (weeds/sqm)	0	(240-448)
clodinafop + additive	30 + 1L	95
fenoxaprop-ethyl	120	43
Isoproturon	2500	68

Application Date: 4/12/91, *A. myosuroides* at GS 12-22 .

In 1993 & 94 the autumn and early winter were so wet that application of the post-emergence treatments could not be made until February. By the time of these applications the *A. myosuroides* was tillering, beyond the growth stage considered to be the optimum timing for application of resistance management treatments, with some weeds present having up to four tillers. Compounding this, the interval between the pre-emergence and post-emergence treatments was four months and early spring growth of the crop provided little competition to the surviving *A. myosuroides*. Nevertheless, the results from the first two seasons was encouraging given the degree of control achieved by fenoxaprop-ethyl (20-30%). Clodinafop-propargyl displayed inherently greater activity at 60-75% whilst the addition of trifluralin or sequence with triallate increased control in each year. In these circumstances, the most successful treatment was the sequence of triallate followed by the mixture of clodinafop-propargyl and trifluralin which provided a commercially acceptable level of control.

In the season 1994-95, the more normal autumn/winter conditions allowed application at the optimal timing and a six week interval between the pre-emergence and post-emergence treatments, this resulted in an improvement in the control from clodinafop-propargyl (90%). The value of mixing clodinafop-propargyl with herbicides with a different mode of action was again demonstrated, the mixture with trifluralin and the sequence of triallate both providing excellent control (97 & 99% respectively). As in the previous two years the combination of triallate sequence with the trifluralin mixture gave the highest result. Interestingly the performance of both isoproturon and fenoxaprop-ethyl was again poor, highlighting the resistant nature of these *A. myosuroides* biotypes to these compounds. Compared to the original application in 1991 (Table 1), the control by clodinafop-propargyl was maintained, whilst that of fenoxaprop-ethyl continued to decline.

This trial will continue for the next five years so as to enable reliable prediction of the performance of the mixtures and sequences in commercial usage and to modify recommendations as appropriate following experience of long term use.

Table 2. Northants Field Development of Resistance Seasons 1992-3 to 1994-5.

Application Date - pre-em*		15/10/92	22/10/93	3/10/94
- post-em		23/2/93	22/2/94	24/11/94
***A.myosuroides* GS (post-em)**		21-24	13-23	12-21
Project & Year		H02 1993	H02 1994	H02 1995
Compound	G.AI/Ha	% Control	% Control	% Control
Untreated (heads/sqm)	0	300	544	1146
clodinafop+additive	30 + 1L	75	60	90
clodinafop+trifluralin+additive	30 + 960+1L	85	70	97
triallate* fb clodinafop+ additive	2250 fb 30+1L	85	92	99
triallate* fb clodinafop+ trifluralin+additive	2250 fb 30 + 960 + 1L	95	95	100
fenoxaprop-ethyl	150**	30	20	0
isoproturon	2500	50	80	10

** in 1994 fenoxaprop-p-ethyl at 69 g.ai/ha.

The resistance status of the *A. myosuroides* biotypes was confirmed in glasshouse studies, Table 3, where seed from surviving plants was sampled in the summers of 1992-94. The resistance to clodinafop-propargyl of seed from plants treated with fenoxaprop-ethyl, clodinafop-propargyl or untreated showed no increased resistance development. However, resistance to fenoxaprop-ethyl in populations previously treated with clodinafop-propargyl or fenoxaprop-ethyl showed an increase relative to untreated populations - 49 & 63% respectively compared to 87% control.

Table 3. Glasshouse Testing of *A. myosuroides* Seed From The Northants Repeat Application Study. Results for seed collected in the summer prior to the indicated field treatment year.

Field Testing Year	**1992-3**	**1993-4**	**1994-5**	**1992-3**	**1993-4**	**1994-5**
	Glasshouse Treatment					
	Clodinafop + Additive 30 g.ai/ha + 1L			**Fenoxaprop 150 g.ai/ha**		
Field Treatment (g.ai/ha)	% Control	% Control	% Control	% Control	% Control	% Control
clodinafop+additive (30+1L)	-	100	100	-	72	49
fenoxaprop-ethyl (150)*	100	98	100	84	67	63
Untreated	-	-	100	-	-	87
(Peldon Standard)	100	90	100	94	90	96

* in 1994-5 fenoxaprop-p-ethyl at 69 g.ai/ha.

Clarke & Moss (1994), describe a resistance rating system based on the fresh weight reduction of populations following treatment relative to Rothamsted sensitive and Peldon resistant standards. This classification was not possible in these studies due to the activity of both compounds against the Peldon biotype - this not being the most "fop" resistant of biotypes. Future studies will utilise a dose response to allow the calculation of ED50 values to more accurately quantify shifts in resistance.

Table 4 presents the results from two trials which have been designed to select for resistance so that the rate of development can be assessed. In future years the effectiveness of the proposed strategy in managing the resistant biotypes can be determined. Both of these sites received diclofop-methyl as the sole method of grassweed control from 1987 to 1990, from 1991 clodinafop-propargyl was employed giving a total of nine years of continued "fop" usage. Applications were always made in the spring until 1994 when the large blocks were sub-divided and autumn treatments of clodinafop-propargyl +/- trifluralin added. After nine years of "fop" usage there are no indications of resistance developing at the Hill Farm site, this has been confirmed by glasshouse testing (unpublished results). At the Elmdon site however, the application in the spring of 1993 showed the first indications of resistance with a further decline following the spring 1994 application. Glasshouse testing of seed from surviving plants in both years indicated an inconsistent and as yet minor shift in resistance. In 1995 the spring application of clodinafop-propargyl showed a further decline in control demonstrating the continued increase in resistance from repeated spring applications. The autumn application of clodinafop-propargyl alone or in mixture with trifluralin provided excellent control. The response to clodinafop-propargyl alone perhaps reflects the, so far, minor changes in resistance status.

Table 4. Long Term Repeat Treatment Sites

1. Hill Farm				**% Control By Year**				
Application Period	Weed GS	Compound	g.a.i./ha	1991	1992	1993	1994	1995
		untreated (weeds/sqm)		100	30-80	40-60	40-100	40-100
Spring	21-55	clodinafop+ additive	30+1L	100	100	100	100	100
Autumn	12-23	clodinafop+ additive	30+1L					100
Autumn	12-23	clodinafop+ trifluralin+ additive	30+ 958+ 1L				100	100

2. Elmdon				**% Control By Year**				
Application Period	Weed GS	Compound	g.a.i./ha	1991	1992	1993	1994	1995
		untreated (weeds/sqm)		100-700	20-100	40-100	40-100	500-1000
Spring	12-31	clodinafop +additive	30+1L	99	100	95	80	40
Autumn	11-24	clodinafop +additive	30+1L					99
Autumn	11-24	clodinafop +trifluralin +additive	30+ 958+ 1L				99	100

DISCUSSION

Trifluralin and triallate were selected as potential components of a clodinafop-propargyl based resistance management strategy on the basis of the modes of action being different from the acetyl Co-A carboxylase inhibition of clodinafop-propargyl. Trifluralin inhibits microtubule polymerization of tubulin (Strachan & Hess 1983) and triallate inhibits the fatty acid synthase complex (Devine 1993). The mechanism of selectivity between the crops and the weeds for these two compounds is not based solely on the rate and type of degradation by the plant as with clodinafop-propargyl (Kreuz 1993). In these respects both herbicides fulfil two of the criteria for successful use of mixtures and sequences for managing resistance as proposed by Wrubel & Gressel (1994).

For a sustainable, successful strategy it is also essential that each component of the mixture and sequence should be active against the target species. Moss (1987a) examined the cross-resistance pattern displayed by a population of *A. myosuroides*, where he found extensive cross-resistance to most cereal-selective grass herbicides including some resistance to the dinitroaniline pendimethalin. This resistance was not expressed to the similar dinitroaniline trifluralin, indicating differences within chemical groups. Triallate has been used in the UK for twenty years with no reports of grassweed control failures due to resistance.

The core chemical component of this resistance management strategy, due to its inherent activity against *A. myosuroides* and flexibility of use is clodinafop-propargyl. The results presented in this paper demonstrate that clodinafop-propargyl when applied in the autumn/winter retains considerable effectiveness against *A. myosuroides* biotypes resistant to the chemically related fenoxaprop-ethyl. The expression of resistance, at least in the biotypes tested, appears to occur slower with clodinafop-propargyl than fenoxaprop-ethyl. These differences between members of the aryloxyphenoxyproprionate class of herbicides ("fops") are not yet fully understood, but may be related to differences in the plant metabolism of these herbicides. In all species, both compounds are subject to ester hydrolysis to yield the herbicidally active acid form. In tolerant species the acid of clodinafop-propargyl is subject to hydroxylation at the pyridinyl moiety and ether cleavage between the pyridinyl and phenyl ring with all subsequent metabolites subject to glycosyl conjugation, (Kreuz, Gaudin, Stingelin & Ebert, 1991). In contrast the acid of fenoxaprop-ethyl is directly subject to conjugation through the displacement of the phenyl group by glutathione and cysteine (Tal, Romano, Stephenson, Schwan & Hall, 1993).

The rate at which resistance to the "fop" herbicides develops, in particular to clodinafop-propargyl is being investigated in the two long term, repeat treatment trials. It has been shown that resistance to fenoxaprop-ethyl (Clarke & Moss 1994), can develop very rapidly and it has been assumed that this will be the case for all "fops". The results to date after nine years of repeated applications suggest that the rate of development is highly variable, presumably being dependent on the frequency of resistant biotypes present in the original *A. myosuroides* population. Certainly for clodinafop-propargyl there are field populations in which resistance development may be rapid, slow or not occur at all.

The mechanisms of resistance of grass weeds to the "fops" is the subject of continuing investigation, however, it appears likely that there are two possible mechanisms; mutation at the target site resulting in an insensitive acetyl Co-A carboxylase, and enhanced metabolism of the herbicide. Target site mutation is likely to be specific to a particular class of chemistry/mode of action type and would cause a very high level of resistance. In contrast, enhanced metabolism would be more likely to result in cross-resistance but at a lower level of resistance. It can be postulated that the mechanism of resistance present is responsible for the rate at which the expression of resistance on a field scale develops. Target site resistance, due to its absolute nature and consistency amongst individuals would be expected to develop very rapidly. In contrast as enhanced metabolism does not usually provide absolute resistance at field application rates and is likely to be present at varying degrees of effectiveness within the population, this mechanism would result in a very much slower development of resistance in the field. As it is not possible to predict the rate of development or the mechanism of resistance present in any specific situation, the resistance management strategy must be effective against all types of resistance.

Moss (1995) has stressed that for the chemical based management of resistance, herbicides should be used in such a manner as to allow their greatest potential to be expressed by ensuring the timing, application rate and method, and soil and climatic conditions are optimal for activity. This is further supported by the results obtained for clodinafop-propargyl based mixtures and sequences, where application under adverse climatic conditions, to weeds at advanced growth stages or in the spring resulted in a lesser performance than applications in the autumn/early winter. These results also highlighted the need for sequential applications not to be separated by more than eight weeks.

Experience from the major cereal growing areas of the world suggest that resistance management programmes are only considered where resistance has become a locally established problem. This may be associated with previously proposed programmes involving increased cost and significant alterations to farming systems. For proactive implementation an anti-resistance strategy should not incur cost penalties, be practical and ensure effective weed control.

On the basis of field and glasshouse studies conducted since 1990, the control of herbicide resistant *A. myosuroides* has been found to be viable and sustainable utilising clodinafop-propargyl with trifluralin for the prevention of resistance development. In situations where resistance is established, this mixture must be supplemented by a sequence utilising triallate applied pre-emergence. In all situations the WRAG Guidelines, in particular with respect to soil cultivations, stubble hygiene, crop drilling date and crop competition must be incorporated in to the resistance management programme.

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NON-CHEMICAL WEED CONTROL IN CEREALS

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ABSTRACT

Whilst herbicides have proved effective in weed control for improved cereal production over the past 50 years, recent environmental and crop management problems have cast doubts over their future widespread use. A reconsideration of management techniques for effective, economic and environmentally sensitive long term weed control in cereals is therefore required. This paper reviews non-chemical techniques based upon management of the whole-farm system, combined with specific, interventionist techniques such as mechanical weeding. The opportunities for uptake of these concepts on modern cereal farms are discussed.

INTRODUCTION

In the past 50 years, the development of synthetic herbicides for the control of weeds in cereals has been very successful. The incidence of annual, biennial and perennial weed problems has been markedly reduced and, combined with improved husbandry and better cultivars, cereal grain yields in Britain of 7-9 $t.ha^{-1}$ have become the norm (Toosey, 1988). Cereal production on British farms has changed during this period. The availability of inorganic fertilizers has removed the need for fertility-building pastures within arable rotations. Many arable farmers have therefore concentrated upon the more profitable cereal crops, especially wheat (*Triticum aestivum*), and their farms have become stockless. Nevertheless, animal production continues to be important in some parts of Britain and, during the past ten years, dairy production has rapidly become associated with fodder maize (*Zea mays*) as a high-quality source of winter silage. In 1994, 96,800 hectares of this cereal were grown in Britain (Anon., 1995) and maize is now classed as a major crop. Production is currently extending towards the northwest of England and into Scotland as more cold-tolerant maize cultivars become available (NIAB, 1995).

The successful growth of all of these cereals on modern British farms has depended upon the use of herbicides. However, a number of problems has prompted a re-think of herbicide use. Biotypes of weed species have emerged in Britain that are tolerant of some modern herbicides. Examples are: chlorotoluron ('Dicurane' or 'Ludorum') for grass weed control in wheat and barley (Clarke & Moss, 1991); and atrazine for general weed control in maize (Roush *et al.*, 1990). Furthermore, the intended soil-residual activity of some herbicides, such as atrazine, and their consequent chemical stability has led to leaching and appearance in water courses. This is discussed by Bacci *et al.*, (1989). The measurement of atrazine concentrations close to permitted limits in drinking water from isolated parts of Britain prompted MAFF in 1994 to limit atrazine use to agriculture and horticulture only, prohibiting its use for amenity purposes. Additionally, there has been increasing concern about the impact of herbicide use on wildlife. Field margins and associated hedgerows in particular are now acknowledged as an important habitat for wild flowers, insects, mammals and birds. Research has indicated that herbicide use can threaten some of these species, particularly wild plants, which are important hosts of insects such as butterflies (Smith H *et al.*, 1993; Dover, 1994).

The reform of the Common Agricultural Policy (CAP) is an added incentive to reconsider the widespread application of herbicides. Indications are that CAP reform will lead to financial pressure upon farmers to reduce their variable costs by reducing inputs (Lee *et al.*, 1994). Herbicides are a large component of variable costs on British farms (Jordan & Hutcheon, 1993) and thus there is likely to be a rationalisation of their use. In this climate of change, farmers need to be provided with information to allow them to make informed decisions about the most appropriate methods of weed control in cereals. This paper attempts to review the options available.

CONTROLLING WEEDS BY MANAGING THE FARM SYSTEM

All good farm managers know that farms are more than just the sum of their component parts: the genetic characteristics of the crop and animal species chosen will interact with soil physical, chemical and biological factors. In turn, all these factors are liable to interact with pests, weeds and diseases and will be affected by climatic variations. Thus, a farm can be considered as a complex assemblage of many interacting components and weeds as merely one of these. Effective long term weed control therefore depends upon managing the farm to reduce the likelihood of weed problems before they become apparent.

Crop rotation

The choice of crop species and the sequence in which they are grown on farms has a profound effect upon weed incidence. Crop rotations are known to have been practised by the Romans in parts of the European Continent from the 1st Century B.C. (Brehaut, in Karlen *et al.*, 1994) and it is thought that it was they who introduced the concept into British farming (Sanders, 1944). Theirs was a simple three-course (three year) design: 1. autumn 'corn' (wheat or rye); 2. spring 'corn' (oats, barley or peas); 3. fallow (grazed until midsummer and then ploughed). The sustainability of this system is indicated by its persistence from about 200-1700 A.D. However, weeds are known to have been a key problem affecting crop yields: an archaeological examination of medieval deposits indicates that mayweed (*Matricaria perforata*) was a typical associate of cereals during this period and seems to have increased in incidence from Roman times (Pretty, 1990).

In the 18th Century, the development of the 'Norfolk four-course rotation' introduced new crops and husbandry methods into British farming. This rotation consisted of: 1. roots (turnips, swede and, after about 1880, kale); 2. barley; 3. 'seeds' (red clover, sometimes with ryegrass, or sainfoin, trefoil, peas or beans); 4. wheat (Sanders, 1944). It revolutionised British farming, allowing an increase in sheep production for meat, milk and wool whilst helping to increase cereal yields. The introduction of root crops was especially important. The extensive cultivation of soil required before and after planting root crops helped to inhibit weed development. Thus, the cereals within this rotation benefitted from reduced competition from weeds. The concept of weed incidence within crop rotations was first discussed briefly by Young (1808). There were few changes in rotation design until 1914, when the necessities of war led to a greater focus on intensive cereal production. This departure from a stable pattern of cropping continued throughout the economic depression of the 1930's and during the 2nd World War. Despite long term studies during the 1950's and 60's on the potential of re-introducing crop rotations (Hanley & Ridgman, 1979) arable cropping sequences have become typically simplified, such as: 1. wheat or barley; 2. wheat or barley; 3. oil seed rape or linseed etc.

Despite the use of herbicides to control weeds in cereals, associated weed species have become quite common: typical grass weed problems include black-grass (*Alopecurus myosuroides),* barren brome (*Bromus sterilis*), meadow brome (*B. commutatus*), and wild-oats (*Avena fatua*); typical broad leaved weeds are cleavers (*Galium aparine*) and volunteer oil seed rape (*Brassica campestris*) (Clarke & Davies, 1995, Hurle 1993). Interest is therefore being re-focused upon crop rotations as a means of inhibiting these and other weed species. Jordan (1992) considers crop rotations to offer "...the most effective, indirect method of minimising pest, disease and weed problems...". Parish (1990a) examines the biology of crop/weed interactions and suggests crops as especially susceptible to competition from weeds between four to ten weeks after 50% crop emergence. Similar 'critical' periods are specified for maize by Morrish (1995). A suitable rotation which may achieve better weed management is suggested by Parish (1990a) as: 3 years grass/clover ley; 2 years winter wheat; 1 year arable silage (cereals/legumes); 1 year potatoes; 1 year spring barley (undersown with ley) etc. The three year ley is noted as being particularly good for controlling annual weeds, so that the wheat which follows can be drilled into a clean bed. Other general points for weed control within rotations are summarised by Lampkin (1990) as: i) the importance of alternating between spring and autumn drilled crops, allowing cultivations for weed control at both times, and; ii) the need for occasional crops which are relatively competitive against weeds, such as potatoes or oats.

A series of farming research programmes in Britain has been undertake (see Table 1 below for summary). These have involved varying all-arable rotation designs. It is difficult to isolate the effects of rotation design from weed control in these programmes and to generalise for so many different sites. Overall, the rotation designs used seem to have been associated with variable weed control, dependent upon management factors discussed below.

Cereal seedbed preparation

The timely and careful cultivation of the seedbed prior to drilling can have a profound effect upon weed incidence (Lampkin, 1990); useful work relates different cultivation systems to likely weed infestation (Froud-Williams *et al.*, 1984, Froud-Williams, 1987). This work is currently being developed further within the LIFE systems project at Long Ashton (Jordan & Hutcheon, 1993).

Cereal cultivar choice

There has been very little work on the relative competitiveness of crop cultivars to weeds. The National Institute of Agricultural Botany has published some information for organic vegetable growers, which briefly considers competitive ability against weeds (NIAB 1989). There have been few studies on cereal cultivar suitability for high and low input production systems (such as Poutala *et al.*, 1993) and very few on relative competitive ability of cereal cultivars (see Grundy *et al.*, 1993, De Lucas Bueno and Froud-Williams, 1994). It is an area worthy of further study.

Seed rates and spacings

Growing cereals in the absence of herbicides may require a reconsideration of recommended sowing rates and plant spacings, since current advice assumes a herbicide-reduced weed incidence. Parish (1990a) notes that higher seed rates are likely to be required for cereals. This is to help the crop compete with any weeds present and also to allow for crop seedling mortality due to tine harrowing (see below). This is supported by experimental work on spring barley (Kirkland, 1993) and winter wheat (Grundy *et al.*, 1993) and for both crops (Wright *et al.*, 1993).

Smother crops

There has been some interest in the 'biological control' of weeds by encouraging the growth of a close carpet of foliage which acts as a living mulch. This will compete with weeds for light, water and nutrients. Maize in the U.S.A. has so far been the major cereal studied. The most successful living mulches for weed control and enhanced maize performance have tended to be vigorous low-growing legumes, such as hairy vetch, *Vicia villosa* (Ess *et al.*, 1994) and white clover, *Trifolium repens* (Werner, 1988). A more general review (Forcella & Burnside, 1994) is less conclusive. Some work on wheat performance with a white clover (*T. repens*) understorey has also been undertaken in Britain, with inconclusive results (Lewis Jones & Clements, 1993). There is clear potential for further investigative research in Britain.

Intercrops

The encouragement of more competitive cereal crop canopies has also been shown to inhibit weeds. Research on wheat (*T. aestivum*)/bean (*Vicia faba*) intercropping in Britain has indicated higher total grain yields than sole crops, combined with better weed inhibition due to shading (Bulson *et al.*, 1990, Lee *et al.*, 1994). Similar results have been observed by the author for rye (*Secale cereale*)/hairy vetch (*V. villosa*) mixtures at Wye College.

Limited tillage

This has been examined in Britain, especially for wheat and barley. It is not reviewed in detail here because it usually relies upon a contact herbicide to kill any weeds before the cereal is direct drilled. Work has indicated that limited tillage has variable potential in Britain, due to problems with perennial weeds like couch (*Elymus repens)*. For a useful review, see Wiese (1985).

Reducing the chances of weed seed build up on the farm

On stocked farms, the use of organic manures is an effective way of recycling nutrients within the farm system. However, there is a risk of contaminating fields with weed seeds that have passed intact through the gut of the animal (Dastgheib, 1989). Composting animal manure kills most weed seeds and is also a good way of utilising waste cereal straw. On stockless farms, clean, well-organised husbandry can help to reduce the risk of weed seed transfer. Even so, weed seed contribution to soil within fields can be a difficult problem, and is often only solved by hand roguing (e.g. wild oats - *A. fatua*).

Weed seed bank estimation for prediction of potential weed problem

There has been much work on the effects of different husbandry systems on weed species diversity and incidence (such as Froud Williams, 1988). More specific research has isolated agronomic factors, such as fertiliser and herbicide applications affecting weed vigour in spring wheat (Grundy *et al.*, 1991) and winter wheat (Lintell-Smith *et al.*, 1991). There have also been many ecological studies on weed seed content of soil in relation to weed flora seen above ground (such as Wilson *et al.*, 1985). Generally, it has been established that there are key factors affecting weed seed germination as a contribution to flora - these include weed seed dormancy, and environmental conditions favourable for germination of different weed species. One complicating factor is that weed seeds may germinate to compensate for the effects of weed removal by tillage, which has clear implications for long term studies such as LIFE (Wilson *et al.*, 1994). Thus, since the factors affecting weed seed germination and subsequent plant development are incompletely understood, it is currently not possible to reliably predict potential weed problems in cereal crops from studies of weed seed banks. This area also warrants further study.

CONTROLLING WEEDS USING SPECIFIC TECHNIQUES

Managing cropping systems to reduce the chances of weed problems may only be partially successful, as indicated above. If so, a range of specific interventionist techniques need to be available for the farmer to tackle a weed problem in the early stages of development.

Weed thresholds

The relative competitive abilities of common weed species have been assessed (Wilson, 1989) and weed threshold studies in cereals undertaken (Davies *et al.*, 1994). However, all of this work has been organised within intensive systems of production and, as Jordan (1993) suggests, may not necessarily be applicable to less intensive whole-system approaches. Further research in such systems is needed.

Inert mulches

This is of interest for weed control in maize. The use of black polythene as a surface mulch is becoming popular amongst maize growers in Britain, partly to allow reliable growth further north, but also because of good weed control properties. Its use is discussed elsewhere (Maize Growers' Association, 1994).

Flaming

This is not currently a popular technique for weed control in Britain, so is discussed here only briefly. Machinery is available which can direct a propane or butane flame from burners positioned in rows on an assembly behind a tractor. This can effectively expose ground to momentary, very high temperatures (90-100°C) as the flame passes over. Exposed weeds suffer severe cell damage and rupture of membranes, leading to plant death within a few days. Although flame weeding is commonly used only within vegetable row crops (Parish, 1990b), it could be used for pre-emergence weed control (Lampkin, 1990) in crops like cereals, although costs might be prohibitive.

Mechanical weed control

The use of some sort of cultivation for weed removal in cereals in Britain has been practised at least since the late 18th Century. Young (1808) and Tull (1822) report that the widely accepted practice at that time was to hand-hoe against weeds in cereals in the spring. Fields would be treated this way once or even twice using casual labour. However, there was some disagreement about the effectiveness of hoeing, with some arguing that more root damage was done to the cereal plant than benefit gained from weed removal (Young, 1808).

In this Century the use of tillage for weed control in cereals disappeared with the advent of herbicides and it is only comparatively recently that there has been a re-examination of these concepts. Work was first reported on mechanical weeding in arable crops from mainland Europe, especially Germany (Geier & Vogtmann, 1988, Brautigam, 1990) and Denmark (Mattson *et al.,* 1990) and specifically in cereals (Rasmussen, 1991). The same is true for early research on mechanical weeding in maize (Buhler *et al.,* 1994). Further definitive research on mechanical weeding in wheat (Berry, 1994) and maize (Morrish, 1995) has been undertaken at Wye College and will be published shortly. Both research programmes indicate that some types of machinery can achieve reliable levels of weed control in these crops, but that timing of use and careful management is also required. Some soil aspects of mechanical weeding have been studied by others. For instance, mechanical weeding in winter wheat seems to have implications for soil nutrient availability, particularly stimulating nitrogen mineralisation (Smith *et al.,* 1994), while, for maize, inter-row cultivation can lead to root damage and reduced performance (van der Werf & Tollenaar, 1993). An economic study of the apparent and hidden costs of mechanical versus herbicide-based weed control in major U.K. arable crops is currently in progress at Wye College (Bradley, *pers. comm.,* 1995).

THE POTENTIAL FOR NON-CHEMICAL WEED CONTROL ON MODERN CEREAL FARMS

Many possible management and specific techniques have been discussed above for non-chemical weed control in cereals. However, much of this work is based upon short term, reductionist trials. Whilst such work has enormous value in assisting the understanding of specific factors, it needs to be complemented by systems-based studies. These are underway in Europe, including Britain. The major British programmes are summarised in Table 1.

Table 1. Major farming research programmes in Britain

Programme title	References
BOXWORTH	Grieg-Smith *et al.,* 1992, Bowerman, 1993.
SCARAB	Bowerman, 1993, Ogilvy, 1995.
TALISMAN	Jordan *et al.,* 1990, Clarke *et al.,* 1993, Ogilvy, 1995.
LINK-IFS	Ogilvy, 1994a,b.
LIFE	Jordan *et al.,* 1990.

These programmes involve the use of management and interventionist techniques for weed control. Rotations are designed to help minimise potential weed problems, whilst mechanical weeding is also used, sometimes combined with reduced doses of herbicides. Lack of space precludes a more detailed review here. However, the information gained from these programmes has been and continues to be of enormous value. These and other systems-based research programmes, combined with specific reductionist trials, should provide British cereal farmers with the information required to make wise and economic choices about appropriate weed control in cereals.

CONCLUSIONS

Non chemical weed control in cereals *is* possible on British farms. Design of appropriate crop rotations and other management strategies can be combined with specific techniques when required to give reliable weed control in a range of situations. However, as for all farming practices, good planning, timeliness and careful husbandry is also essential. The occasional use of herbicides at reduced doses may sometimes also be appropriate and current farm research programmes should help the farmer to clarify this.

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WEED MANAGEMENT STRATEGIES FOR SMALLHOLDER RICE PRODUCTION.

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ABSTRACT

Rice is grown within a wide range of ecologies, the diversity of which is reflected in the weed problems facing farmers and the control measures used. A common feature however, is that smallholders with limited resources, form the majority of producers. In most traditional systems, farmers use combinations of control measures, depending on the system and the resources available. In many regions, particularly in upland rice, traditional weed control methods prevail, and long periods of fallow between crops are a vital part of farmers' weed management strategies. In such extensive systems, weeds are considered to be a major constraint to sustainable intensification. In contrast, the irrigated lowland systems of Asia allow sustained intensive production, and here there have been considerable advances in weed control technology. These have enabled a shift, in some areas, from transplanted to direct seeded systems.

The paper emphasizes weed management in rice-based cropping systems of sub-Saharan Africa. The nature of weed problems for smallholder rice farmers and established weed control methods are described. Despite the widespread use of herbicides, these technologies remain unavailable to many farmers, often due to a lack of resources. Development of weed control measures for resource-poor farmers requires that greater emphasis be placed on low cost weed control technologies and the integration of cultural control methods. Development of improved fallows, competitive rice varieties and agronomy are some options discussed.

RICE CULTIVATION

Rice is grown throughout the world in rainfed uplands, seasonally deep flooded areas, mangrove swamps and irrigated lowlands. Table 1 shows regional rice yields (t/ha) compared to total population and the annual increase in the area cultivated to rice. The regional average yields conceal substantial variations between countries. For instance, in West Africa the national average yields vary between 0.83 to 3.96 t/ha, depending upon whether low-input upland or irrigated lowland systems predominate (WARDA, 1993). In West Africa, the area under rice cultivation is increasing but at an insufficient rate to meet growing domestic demand, resulting in an annual average increase in the level of imports of 6.8% between 1970 and 1990 (WARDA, 1993).

Table 1. Regional Rice Production (IRRI, 1995).

	Popln. 1991 (mill.)	Share of the labour force in agriculture	Annual % growth in rice area	Yield (t/ha)
Asia	3,157	60	0.30	3.7
Latin America	445	26	-2.43	2.8
Africa	645	63	2.63	2.1

Upland systems

Almost 100 million people depend on upland rice as their staple, including some of the world's poorest farmers (Arraudeau, 1995). In West Africa, upland rice comprises 57% (1.8 million ha) of the total rice area. Upland rice grows in diverse systems, ranging from shifting cultivation to relatively intensive systems, utilizing hand tillage, animal or mechanized traction and rotations with other crops, including cotton, legumes and other cereals. Shifting cultivation occurs throughout the humid forest zone, where land is cleared from forest, usually by slash and burn, and rice is grown for one or more seasons before the land is returned to fallow. Invasion by weeds is a principal reason for abandoning land after periods of cultivation (Sanchez & Benites, 1987). Upland rice is dibble, broadcast, or row seeded, the former being commonly used in shifting cultivation. The most common method of weed control is by hand, often with the aid of hoes or machetes. In Asia, Africa and many parts of Latin America the crop is typically grown with few, if any, purchased inputs.

A wide range of weeds infest upland rice, many of which are pan-tropical, including *Digitaria* spp., *Echinochloa colona, Eleusine indica*, *Paspalum* spp., *Commelina* spp., *Ageratum conyzoides*, *Portulaca oleracea* and *Amaranthus* spp. The composition of weed communities depends on the ecology and the cropping system.

Lowland systems

Lowland systems involve various levels of land development, enabling rainfall to be retained or irrigation water supplied to flood the rice crop. Systems with effective water control present the greatest technical opportunities for intensification and diversification. Flooding usually improves soil chemical conditions and limits the growth of weeds, though in direct seeded systems, post-emergent weed control is usually essential.

Marnotte (1993) reported that weed infestations in irrigated rice in Mauritania were exacerbated by poor land levelling and preparation, inadequate water management, irrigation water and rice seed contaminated with weed seeds, direct seeding, and no crop rotation. A similar situation prevails in many other parts of the region. In West Africa, of the 20-50 million ha of inland valley bottoms and hydromorphic fringes, only about 15% are currently utilized (Terry *et al.*, 1994). Appropriate weed control regimes are a vital component of sustainable development for these areas.

The most serious weeds of lowland rice are pan-tropical and the more widespread include sedges, such as *Cyperus difformis*, *C. iria*, *Fimbristylis* spp. and *Scirpus maritimus*, the grasses *Echinochloa* spp, *Ischaemum rugosum* and *Oryza* spp., and the broadleaves *Ludwigia* spp. and *Sphenochlea zeylanica*. These weeds are well adapted to the aquatic environment, capable of rapid growth and multiplication and are very competitive with rice. The similarity of some weeds, such as *Echinochloa* spp. and *Ischaemum rugosum*, to rice at early stages of growth makes it very difficult for farmers to distinguish them while hand weeding.

Mangrove and deep water production systems are limited to specific environments, though they share some of the weed control problems with the lowland systems above; others such as the rhizomatous grass *Paspalum vaginatum* in the mangroves, are more specific.

The widespread occurrence of many of the more serious rice weeds should, at least partly, be blamed on the distribution of rice seed contaminated with weed seeds. In this way, species such as *Oryza* spp., *Ischaemum rugosum*, *Echinochloa* spp., *Rottboellia cochinchinensis*, and *Euphorbia heterophylla* have been introduced into new areas. Further, in the lowland rice systems weeds may be rapidly spread via the irrigation water.

LOSSES DUE TO WEEDS VS OTHER PESTS

In a survey of upland rice producing countries covering 80% of the total production area, Arrandeau and Harahap (1986) found that weeds were the most widely reported biological constraint to yields. This is congruent with a survey of farmers in Côte d'Ivoire, which showed that farmers regarded weeds as the major pest of rice (Johnson & Adesina, 1993). Upland rice, in particular, competes poorly with weeds and uncontrolled weed growth often results in negligible or zero yield. Losses due to uncontrolled weed growth in upland rice in India were up to 90% (Sahai *et al.* 1983), and in both lowland and upland systems in Africa losses were within the range 28-100% (Akobundu & Fagade, 1978). Two years after clearing a fallow in Central America, yields of upland rice with no weed control were less than 20% of those when the crop was hand weeded twice after sowing (Johnson et al. 1991). In West Africa, yields of upland rice with farmers' weed control, were 44% lower than on researcher weeded plots (Heinrichs *et al.*, 1995).

Losses in direct seeded lowland rice can be particularly severe, as the rice and weed seedlings are at similar growth stages, preventing the use of early flooding to limit weed establishment and increasing the risk of damage to rice with post-emergence herbicides. Further, where the crop is broadcast seeded rather than in rows, hand weeding is extremely time consuming. Losses in transplanted rice tend to be less than those in direct seeded rice, because young plants have an advantage over germinating weeds and immediate flooding after transplanting limits the establishment of many weeds. In Asia, yield losses due to uncontrolled weed growth in wet seeded and transplanted lowland rice were 64 and 57% respectively, though it is rare for farmers not to undertake some weed control and therefore losses on farmers' fields are likely to be considerably less (Moody, 1990).

CONTROL METHODS

Flooding is the most effective method of cultural control of weeds in rice (Wells, 1992). Flooding to a depth of 10 cm prevents germination of most weed seeds and kills the majority of weed seedlings. Normally, flooding is used in conjunction with other control measures, such as herbicides or hand weeding. However, for flooding to be successful, water levels must be maintained and fields well levelled to ensure an even depth of water. In many smallholder schemes, limited irrigation water and poor land development can be major constraints to effective weed control.

Tillage serves to provide a suitable soil tilth for a seedbed and control weeds prior to crop establishment. In smallholder systems, practice varies from zero tillage, as in many of the systems of shifting cultivation, to repeated deep cultivation to remove troublesome perennial weeds, such as *Oryza longistaminata*. Shallow tillage is often ineffective in controlling weeds (Le Gal, *et al.*, 1990) and, regardless of tillage practice, some post emergent weed control is normally necessary.

Hand weeding

Hand weeding is the most widely used weed control method, with availability of labour being the main limitation to effectiveness. In some areas, adoption of line planting in transplanted rice has allowed the introduction of rotary weeders for cultivation between rice rows, considerably reducing labour requirements for weed control (Wells, 1992). Singh and Ghosh (1992) reported that weeding at 15 and 30 DAS gave a 60% increase in yield over a single hand weeding at 30 DAS. However, because hand weeding is laborious, with labour sometimes expensive and in short supply, weed control is often imperfect and/or delayed. In a survey of rice farmers in Côte d'Ivoire, 53% said that their fields were not always weeded, with the most common explanation being that weeding was not considered worthwhile due to severe weed infestation, thus effectively abandoning the crop (Johnson & Adesina, 1993). Further, 80% of farmers said that if weeds were less of a problem they would increase the area of land under cultivation. Several constraints limit the effective use of hand weeding, including household labour constraints, limited cash for hiring labour, and labour not being available for hire during peak periods. In a village survey in Côte d'Ivoire, where no herbicides were used, farmers spent 408 and 506 h ha^{-1} hand weeding upland and lowland rice, respectively (Ouattara, 1994). In Asia, weed control in upland rice can require 32 - 198 man days per ha, representing 17 - 57% of the total labour requirement for the crop (Kon, 1993). The availability of animal traction can alleviate the constraints posed by reliance on hand labour. Technology including an animal drawn row seeder and hoes, enabling mechanical weed control, may be an appropriate package where animal traction is a possibility (Adesina, 1992), although problems have been encountered with the operation of seeders under farmer conditions.

Fallow systems

Moody (1975) suggested that the greatest constraint to continuous cultivation in the tropics is man's inability to control weeds, a particularly acute constraint for farmers with limited resources and little access to appropriate technologies. After initial clearance of the forest, weed growth consists largely of broadleaved weeds and forest regrowth, though with repeated cropping, more problematic grasses invade the fields (Moody, 1982). Studies have shown that weed growth following a fallow of less than three years was almost twice that following a fallow of five or more years (Heinrichs *et al.* 1995). Where the cropping cycle is short compared to the length of fallow, forest rapidly regenerates from seeds, roots and cut stumps. However, repeated cultivation allows invasion by annual and perennial weed species and replacement of native forest species by weeds such as *Imperata cylindrica* and *Chromolaena odorata*. While these particular weeds are generally considered serious weeds, Dove (1986) reported that Indonesian farmers viewed them as desirable fallow species when they occurred in semipermanent cultivation systems with short grass fallows or in short rotation bush fallow systems. Indeed, in West Africa, Heinrichs *et al.* (1995) reported that farmers were not necessarily concerned about the invasion of *Chromolaena odorata* and recognized that it had some benefits, as it was easy to cut and that it smothered other, more serious weeds.

While shifting cultivation has been criticized as being wasteful of land and forest resources, it is still the main means of production for many resource-poor farmers. In such systems, the fallow period is an integral part of the cropping cycle. In many areas where shifting cultivation is practiced, the soils are inherently infertile. Cropping intensification on such areas therefore, requires technologies to address increased weed pressure and declining soil fertility, if such systems are to remain sustainable. Research has aimed at improving fallows, often utilizing legumes to enhance soil fertility (particularly nitrogen status), reduce weed growth and protect the soil from erosion (Carsky & Ajayi, 1992; Akobundu, 1992). Legumes species considered as possibilities for rice-based systems have included *Calopogonium mucunoides*, *Pueraria phaseoloides*, and species of *Sesbania* or *Aeschynomene*. Research to evaluate legumes for benefits to soil physical and chemical properties have not been matched by studies on their effects on weed infestation over time. However, there are promising examples of success with the control of *Imperata cylindrica* using *Mucuna pruriens* in maize cropping systems (Versteeg & Koukopan, 1990). As with other food crops, these options not only have to be technically feasible but must also be congruent with the farmers resources and aspirations.

Crop competition

Reducing the distance between rows or hills, has been shown to reduce weed infestation in rice in upland, hydromorphic and lowland ecologies (Johnson *et al.*, 1991; Akobundu and Ahissou, 1985; Heinrichs *et al.* 1994). In irrigated lowland systems of West Africa, seed rates up to 100 kg/ha have been reported to control weeds (Le Gal *et al.*, 1990). However, increased plant populations are only achieved at increased costs of labour or seed.

The outcome of crop-weed interaction is largely determined by competition for light, water and nutrients. Of these, nutrients, and nitrogen in particular, may be most readily managed by farmers. Weeds usually have higher growth rates and nutrient demands than rice, hence the amount and timing of fertilizer application can significantly effect weed-rice competition. Interactions between crop and weeds, both above and below ground, are complex and still relatively poorly understood, so that few firm recommendations for smallholder farmers have emerged. Studies on allocation and competition for resources within the crop would assist the development of low-input technologies suitable for the smallholder. Application of crop modelling techniques may greatly assist the understanding of these interactions (Kropff *et al.*, 1993).

With the introduction of "modern", higher yielding rice varieties, it became apparent that in some cases they were less able to compete with weeds than many of the traditional rice varieties they were intended to replace. The ability of rice to compete with weeds is positively correlated with grain yield under conditions of low nitrogen status, wide spacing, and poor weed control, and negatively correlated with grain yield under conditions of high plant density, high nitrogen levels and good weed control (Kawano *et al.*, 1974). Rice varieties best suited to the former situation were tall, of long duration and with high vegetative vigor, while the latter situation favoured plant types combining short stature, short growth duration and erect leaves. This suggests that increases in yield potential of modern rice varieties compared to tall, leafy traditional varieties has been achieved by sacrificing their competitive ability with weeds. The lack of weed competitiveness in modern varieties may be one reason that many upland rice farmers have retained traditional varieties. Recently, the competitive ability of different rice has become a focus of research, with the intention of combining competitive ability with other desirable characteristics in order to develop varieties suitable to low-input conditions. Studies on different plant types show that tillering ability, height, leaf canopy and root development may be important factors in determining the competitive ability of rice plants (Garrity *et al.*, 1992; Fofana *et al.*, 1995). These studies have shown substantial differences in the weed growth between the least and the most competitive rice varieties tested. The development of weed competitive rice varieties, could make a substantial contribution to weed management for resource poor farmers. The challenge for breeders will be to combine these characteristics with other desirable traits, without losing all the gains in yield potential achieved with "modern" varieties.

Other topics of varietal development related to weed control include host plant resistance to the parasitic weed, *Striga*, and the possibility for utilizing allelopathic activity. Rice cultivars resistant to *Striga*, a localized problem in some savanna areas of Africa, have been identified and field tested, providing a potential solution for affected areas (Harahap *et al.*, 1993; WARDA, 1995). Javanica type rice, *O. glaberrima*, and wild rices have been suggested as possible sources of allelopathic activity, which could be transferred into commercial rice cultivars (Fujii, 1992, Arraudeau, 1995). While the utilization of allelopathy could have considerable potential for low input weed management regimes, the availability to the farmer of such technology is not likely to occur in the near future.

Chemical control

De Datta (1972) reported that formulations of 2,4-D and MCPA were effective in controlling annual weeds in transplanted rice, while granular formulations of the selective herbicides butachlor and benthiocarb were effective in direct seeded rice, as alternatives to hand weeding. Subsequent development of herbicides which are safer to use in rice have allowed much greater flexibility in application. In Asia, seed treatment with bensulfuron and pretilachlor + fenclorim, gave effective control of weeds as did pouring the concentrated herbicides directly into 1-2 cm of standing water a few days after seeding (Mabbayad & Moody, 1992). Formulations allowing the application of herbicides directly to irrigation water without the use of spraying equipment have advantages for the small farmer and have become established practice in many areas. Development continues, with an example of the introduction of a low rate mixture of cinosulfuron and pretilachlor in a water soluble bag, enabling safer use (Kon, 1993).

Early confidence in herbicides was well-founded, and development of these technologies has been a major contributory factor in the rapid expansion of direct-seeded rice in Asia (De Datta, 1986). Elsewhere, the use of herbicides in rice has also increased. Herbicides are one of the first labour saving technologies to be adopted as labour costs rise (Adesina, 1992). In 1992, 23% of herbicides used in Côte d'Ivoire were used on rice, with only the cotton crop receiving a greater proportion, 37% (Winrock, 1994). However, only 2% of farmers in a survey in Côte d'Ivoire relied exclusively on herbicides; 24% of rice farmers utilized herbicides in combination with hand weeding (Johnson & Adesina, 1993). These farmers tended to be those farming lowland areas and/or members of cooperatives. Reasons for not using herbicides were because they lacked sufficient funds, lacked knowledge about their use, preferred traditional methods or that herbicides were not locally available.

Analysis of the social profitability of using herbicides in the Philippines indicated that the use of thiobencarb and 2,4-D had a benefit to cost ratio of 16 compared to 3.3 for two hand weedings (Naylor, 1994). Sensitivity analysis on this data showed that the benefit to cost ratio of the two weed control methods would be equal if the true opportunity cost of labour was $0.5/ day rather than $2 /day. Such labour costs might be a reasonable for countries such as Bangladesh that have limited opportunities for rural unskilled labour and where rice is usually hand weeded. In such areas, an implication of adoption of herbicides may be that, with few alternatives, rural unemployment would increase.

With frequent use of herbicides some weed populations have evolved herbicide resistance. In the USA, 30 years of propanil use resulted in resistant *Echinochloa* sp., and after four years of continuous use, bensulfuron resistance emerged in four aquatic weed species (Hill *et al.*, 1994). In Costa Rica, *Ixophorus* sp. and *Eleusine indica* were found to have evolved imazapyr resistance after about five years of herbicide use (Valverde *et al.*, 1993). Studies suggested that selected biotypes of *Ixophorus* were between 5 to 80 times more resistant to imazapyr than the most susceptible biotypes. The evolution of herbicide resistant weeds is a real threat to effective weed control where herbicides frequently used. Smallholder systems may be particularly vulnerable as herbicide are often not used at appropriate times or dosages, which may hasten the development of resistance.

Many rice production systems rely on herbicides for weed control. Heong *et al.* (1995) suggested, that because of the need to reduce costs, and the evolution of new weed problems and herbicide resistant ecotypes, the reliance on herbicides should be diminished by integrating cultural control with judicious use of herbicides. In 1972, Parker, while recognizing the importance of herbicides, suggested that weed scientists should not be simply herbicide scientists. More than twenty years on, such a comment is more pertinent than ever. There have been substantial developments in herbicide technology, with a wide range of pre- and post-emergence herbicides now available to farmers. Improved selectivity and formulations allow safer, easier and more flexible application. However, for many smallholder farmers with limited resources these improvements have had little or no impact. Herbicide development and the results that can be achieved have been spectacular, but comparatively little research has been focussed on cultural weed control. Greater research attention is required on the development of cultural weed control measures and the integration of these with herbicide use. Not only would this assist those farmers who rely on cultural measures, but where herbicides are appropriate, it may allow farmers who have not yet benefitted from herbicide use to do so. However, it is likely that a substantial proportion of the small rice farmers in West Africa, particularly those farming the uplands, will for the foreseeable future continue to rely on weed control methods other than herbicides. Factors mitigating against adoption will continue to be; insufficient funds, inadequate technical support and supplies, an insufficient cost:benefit ratio to cover the investment risk, and a preference for traditional methods. For such farmers, improved control measures which build on traditional practice and which are compatible with farmer resources, may be more appropriate. Such regimes may include improved fallows and rotations, to prevent the ingression of problem weeds which is likely to occur with increasing land pressure. Varieties which are able to compete with, or tolerate weeds, optimal plant populations, and appropriate timing and supply of nutrients are components which would allow the crop to be more competitive with weeds. While many of these topics have been studied as components, studies on the effects of their integration on weed growth in the crop has, as yet, been inadequate. Such measures do not exclude herbicide use, indeed they may be complementary, but they would provide options for farmers to improve returns to labour.

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WEED CONTROL IN INDUSTRIAL CROPS

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ABSTRACT

For a number of independent but interacting reasons there has been an upsurge in interest and production of industrial crops in agriculture. Weed control in such crops commonly, but not without exception, follows the pattern of weed control in existing food crops. In the longer term as more uses are developed for a range of plants in industry, there may be economic difficulties in developing agrochemicals for industrial crops of small area: development production costs may simply exceed potential sales revenue. Hence novel weed control strategies may need to be developed if such crops are to succeed. Volunteer plants from crop species may pose particular problems.

INTRODUCTION

There has been considerable interest and impetus in the development of industrial crops in recent years. This has been the result of a number of factors operating both individually and interactively.

The revision of the Common Agricultural Policy (CAP) in the European Union (EU) introduced the concept of world pricing of commodities to crops that had hitherto been supported on a tonnage basis and compulsory set-aside linked to the payment of aid. This requirement was initially set at 18% for rotational set-aside although because of high wheat prices has since been reduced to 12% and anecdote suggests may be reduced further as an incentive to increase wheat supply and thereby reduce prices.

Whilst set-aside land could remain uncropped, regulations were introduced (MAFF, 1995a and b) to permit the production of non-food crops. Hence in UK, in principle 600,000 ha became available for industrial crop production and in EU 12 6.3m ha were released.

At the same time, considerable steps forward have been made in the field of genetic manipulation of plants, so that exotic genes encoding for products that would not normally be produced in arable crop species, can now be produced. In UK it is probable that the first and industrial crop will be high lauric acid rapeseed.

In addition to the foregoing two other issues have played a major role in developing industrial crops. Of these the first has been the general drive towards bioreplaceability and the production of products from the renewable, rather than finite resources.

Table 1: Estimates of cropping for industrial use in EU 15 and UK

	'000 ha (1995 harvest)	
	EU-15	**UK**
'00' rapeseed	}6340*	73.535
High Erucic Acid Rapeseed	}	13.247
Flax	103	18
Hemp	10	1
Linseed	312*	7.908
Miscanthus	<1	No data available
Short Rotation Coppice	No Data available	230 (ha)
Evening Primrose	No Data available	149 (ha)

Source: EC (1995)

* 1993/94 data.

This has been particularly noticeable in Germany and parts of Scandinavia. Secondly, in UK, the then Minister of Agriculture, the Rt. Hon Gillian Shephard, MP announced a novel crops initiative and consultative document during July 1994 (MAFF, 1994).

LIKELY INDUSTRIAL CROPS

Table 1 indicates current production areas for industrial crops in EU-15 and in UK. However these species are not new to the areas in which they are grown although species such as Miscanthus have hitherto been ornamental rather than extensively produced agricultural species.

Makepeace (1993) proposed a list and grouping of species likely to be grown in UK and Askew (1993) reported a wider range of species that would be grown in EU-15. These are shown at Table 2.

Additionally, Murphy (1995) has indicated that a wide variety of transgenic rapeseeds will become available over the next 15-20 years and that rapeseed (*B.napus*) will be a primary recipient of novel transgenes.

Clearly a number of new species will be introduced to agriculture and further diversity in plant products from rapeseed will occur. The weed control challenges associated with these developments are not yet fully identified.

WHY CONTROL WEEDS ?

The evidence of benefits to crop production from weed control are well established and well documented. A large number of experiments report yield benefits, for example, in wheat (Makepeace, 1982; Hubbard, 1982; Wilson, 1982; Keen, 1991;

TABLE 2: The Use and Relationship of Industrial and Energy Crops to Existing Crops is as follows:

FUEL CROPS	**BOTANICAL FAMILY**
Coppice (*Salix & Populus spp.*)	Salicaceae
Elephant Grass (*Miscanthus sinensis*)	Gramineae
Whole crop cereal (*Triticum aestivum*)	Gramineae
FIBRE CROPS	
Hemp (*Cannabis sativa*)	Cannabinaceae
Flax (*Linum usitatissimum*)	Linaceae
Kenaf (*Hibiscus cannabinus*)	Linaceae
OIL CROPS	
Oilseed Rape (*Brassica napus*) for rape methylester	Cruciferae
Oilseed Rape for erucic acid	Cruciferae
Oilseed Rape for lauric acid	Cruciferae
Oilseed Rape for stearic acid	Cruciferae
Linseed (*L. usitatissimum*) Industrial Oils	Linaceae
Linola - oleic acid	Linaceae
Sunflower (*Helianthus annus*) oleic acid	Compositae
Crambe maritima - pharmaceutical oil	Cruciferae
Honesty (*Lunaria biennis*) - pharmaceutical oil	Cruciferae
Cuphea spp - lauric acid	Lythraceae
Gold of pleasure (*Camelina sativa*) - pharmaceutical oil	Cruciferae
Caraway (*Carum carvi*) - pharmaceutical oil	Umbelliferae
Borage (*Borago officinalis*) - linoleic acid	Boraginaceae
Evening Primrose (*Oenothera biennis*) - linoleic acid	Onagraceae
Naked Oats - pharmaceutical oil (*Avena sativa*)	Gramineae
Coriander (*Coriandrum sativum*)	Euphorbiaceae
Castor (*Ricinus communis*) - versatile oil	Euphorbiaceae
Meadowfoam (*Limanthes alba*) - versatile oil	Papaveraceae
ALCOHOL FUEL ADDITIVES	
Potatoes - ethanol	Solanaceae
Sugar beet - ethanol	Chenopodiaceae
Cereals - ethanol	Gramineae

Sources : Askew, 1993; Makepeace, 1993

Peters *et al*, 1993), and in sugar beet (Farahbakhsh & Murphy, 1986; Breay, 1986; Whitehead *et al*, 1986). Obviously parallels will occur in industrial crops.

Additionally a number of crops carry marketing specifications that preclude or limit impurities, for example, oilseed rape (admixture 2% maximum by weight). Clearly these also apply in many instances to industrial crops.

However, some industrial crops have different requirements. In the longer term pharmaceuticals will be harvested from industrial crops; in this instance extremely high purity of product will be required, probably through a combination of very efficient weed control and extensive but relatively expensive extraction and purification procedures. A very minor level of pernicious weed infestation in a crop from which high levels of purity are required may demand a comprehensive weed control programme.

WHICH OPPORTUNITIES ARISE FOR WEED CONTROL?

In general principal weed control in industrial crops will follow the same pattern as that in food crops. Opportunities which arise are

(i) Stale seedbed - especially for spring sown crops of vigorous species

(ii) Selective weed control - for use where weeds emerging in the crop may be competitive and /or contaminant

(iii) Desiccation - to aid harvesting and remove contaminants

(iv) Transgenic - where a herbicide tolerance trait is introduced into industrial crop. In principle non-transgenic plants of the same species could be removed from a mixed plant stand.

WEED CONTROL IN SPECIFIC INDUSTRIAL CROPS

Fuel Crops

Poplar (*Populus* spp) and Willow *(Salix* spp*)* for Short Rotation Coppice (SRC)

The extent to which weeds affect yield and quality of tree species grown for short rotation coppice has been reported by Scott (1980) who identified simazine as a useful control of germinating weed and Lawrie & Clay (1989) who confirmed the use of glyphosate as a post - emergence weed control. Parfitt and others (1992) reported a range of residual herbicides which were suitable for weed control in SRC. However, under EC regulations the use of residual herbicides is prescribed on set-aside land and weed control there would need to be undertaken with foliar - acting herbicides. Makepeace (1993) suggested programmes including glyphosate, cycloxydim and fluazifop-p-butyl and Clay & Dixon (1993) described pot experiments to ascertain effects of a range of leaf - acting herbicides upon species suitable for SRC.

One area that has yet to be fully evaluated is that involving the re-entry of land which has been used for production of SRC into the arable rotation; a combination of mechanical and total chemical weed controls with glyphosate would appear to offer a solution.

Miscanthus spp.

Miscanthus spp. are perennial plants in UK and NW Europe ; Miscanthus stands are established from transplants. Costs of transplants is currently relatively high and therefore the initial cost : benefit from weed control is wide. Once established, weed control assumes a much reduced significance.

Speller (1993) reported Miscanthus to "suffer post-transplanting shock", especially where plants had been micro-propagated. Hence early establishment weed control would need to be a combination of preplanting removal of perennial weeds (e.g. *Elymus repens*), followed by stale seedbed technique and/or mechanical methods. However where early stands were well established and appeared robust experiments showed them to be resistant to hydroxy benzonitrile herbicides, fluroxypyr, MCPA and clopyralid. Atrazine was also successfully tested but could not be used on set-aside.

Once established, Miscanthus forms annually a dense, vigorous canopy approximately 2m in height. At that point traditional "in-crop" weed control is unnecessary and impracticable to apply. The removal of any persistent weeds from established crops could therefore only be undertaken in Spring before vigorous growth begins or post harvest. This latter may offer the best opportunity although weed growth may be limited at that time of the year; Green (1976) suggested glyphosate to be appropriate at 1.4 kg/ha.

Cereal crops

Because of its higher yield potential winter wheat is likely to be the major fuel cereal. Generally the evidence for weed control in cereals, particularly winter wheat is well documented (see earlier) and there are no reasons to believe that cereals grown as whole crop fuels would need different weed control programmes. However, because fuel crops are sold on commodity markets, cost:benefit of weed control programmes may need review and lower cost agrochemicals be the first choice for use upon them

Fibre crops

Hemp

The potential for the hemp crop to produce fibres and shiv for a range of markets in Europe and elsewhere is enormous. However with current low THC cultivars (THC is a cannabinoid which has psychotropic effects upon humans when ingested in quantities found in high THC clones like Skunk) area of hemp is relatively small (see Table 1). Hence little specific research has been targeted towards weed control in fibre hemp.

In UK hemp is sown during the latter part of the month of April. Once established, growth is rapid and vigorous, hemp crops reaching 2.5m in height at flowering during August. Limited experience suggests weed control to be unnecessary in these circumstances although if hemp were to be grown in situations of high weed density, for example on fen, where populations of 1400 weeds/ m^2 have been reported (Cussans,1989) weed control during establishment may be necessary but awaits evaluation and development. In normal mineral soil situations weed populations are unlikely to reach these proportions and seedbed preparation, perhaps linked to stale seedbed techniques of weed control should prove to be adequate.

Flax

In a comprehensive review of weed control in linseed Lutman (1991) reported experiments showing both dicotyledonous weeds and volunteer cereals to reduce the yield of linseed and flax. Additionally contamination/quality problems were recorded where tall weeds occurred in flax. *Cirsium arvense* (creeping thistle), *Polygonum convolvulus* (black bindweed), *Fumaria officinalis* (common fumitory), *Chenopodium album* (fat hen) and *Polygonum aviculare* (knotgrass) were "not easy" to control.

Additionally the differences in field agronomy allied to harvesting technique are likely to create some problems for UK flax growers relative to Continental European counterparts. In UK the tendency is to lower plant populations than in other countries; that allows combine harvesting rather than pulling. However lower crop plant populations are less competitive with weeds than higher populations.

Kenaf

The production of Kenaf in UK is unlikely in the short or medium term but in more southerly parts of Europe it will be a realistic option. Weed control requires examination.

Oilseed Crops

Oilseed crops appear to command a leading position in industrial crops at present ; it seems unlikely that this situation will change in the next 10-15 years.

Oilseed Rape

It was reported earlier that oilseed rape is already a major industrial oil crop and during the next decade has the potential to develop even further as new modifications are made to its fatty acid composition.

Since unit cost is the driving element in selection of industrial oils it seems likely that winter oilseed rape will be the best economic option for growers. With the exception of volunteer rapeseed from cultivars of different fatty acid composition from that being grown, there is no reason why, in principle weed control should be any different from that in conventional ‘00’ rapeseed. These latter have been well documented (e.g. Ogilvy, 1989; Bowerman, 1989; Lutman, 1989; Sansome, 1989).

Linseed

Being the same species as flax, principles of weed control in linseed are broadly similar. However, linseed cultivars are shorter than flax cultivars and therefore more prone to vigorous, tall growing, weeds. Pouzet and Sultana (1991) found linseed to be very sensitive to competition from weeds and that chemical weed control was essential under French conditions. Most effective treatments in France were bentazone and chlorsulfuron and linuron for dicotyledonous weeds and fluazifop-p-butyl, quizalofop ethyl and haloxyfop - ethoxyethyl for graminaceous weeds.
Frieson (1986) showed that weeds reduced yield of linseed in 96% of experiments whilst 10 -20% ground cover by graminaceous weeds reduced yield up to 80% (Friesen, 1988) and volunteer cereal had the propensity to reduce yields of linseed by 50 - 60% (Friesen *et al*, 1989). Lutman (1991) reported *C. album* (fat hen) , *Poa annua* (annual meadowgrass), *P.convolvulus* (black bindweed), *Sinapis arvensis* (charlock), *Galium aparine* (cleavers), *F.officinalis* (fumitory), *Viola arvensis* (field pansy), *P. aviculare* (knotgrass), *Veronica spp.*(speedwell) and *Cirsium spp.*(thistles) as the main weeds of linseed.

Sunflower

Sunflower oils could be used for both industrial and food markets depending upon fatty acid composition and market specification. The current UK area is small but increasing (circa <1000 ha) and market potential is 40,000 ha per annum (Church & Rawlinson, 1991). In ADAS experiments at Boxworth Research Centre, trifluralin and pendimethalin have given effective weed control although stale seedbed techniques of weed control and inter-row cultivation have proven equally effective but cheaper (Cook, 1994).

Considerable evidence has been accrued on significance of weeds and weed control in France by CETIOM (CETIOM, 1993) and that would apply to all crops, whether destined for food or industrial use in France.

MISCELLANEOUS MINOR OILS

For the purpose of this paper this group includes :

C. maritima (Crambe)
L.biennis (Honesty)
C. sativa (Gold of Pleasure)
C. carvi (Caraway)
B.officinalis (Borage)
O. biennis (Evening Primrose)
C. sativum (Coriander)
R.communis (Castor)

L.alba (Meadowfoam)
Cuphea spp

The taxa listed embrace several plant families, including *Cruciferae, Umbelliferae, Boraginaceae, Onagraceae, Euphorbiaceae and Compositae* ; in UK and much of Europe, crops are at an early stage of development and / or are established but have relatively small areas at present. Consequently critical weed control data and products for weed control are often not elucidated. Due to the economics of markets it is unlikely that anyone would develop full approvals for individual species. However where species belong to plant families that contain other well established crop plants there will be the option to develop herbicide uses based upon experience with established crops and assayed against novel species before "off-label approval".

Additionally, where species have or become adapted to UK or other European conditions critical data from other parts of the World could be used as a basis to test herbicides (e.g. meadowfoam and crambe in USA ; castor from Middle East, South East Asia or Africa)

Whatever approach is used, it has to be concluded that identification and development of useful industrial crop species will occur in advance of identification and certainly approval, even as "off label" approval, of herbicides. Moreover the cost element of herbicides will be a key criterion for selection for use on all but very high value / small market crops.

ALCOHOL FUEL ADDITIVES

The species involved, potato, sugar beet and cereals,will require similar weed control programmes to conventional food crops, although cost : benefit responses may be different and that will affect choice of herbicide.

Programmes for weed control in potatoes are well documented (e.g. Askew, 1986 ; Lawson & Wiseman,1986) and examples of those for cereals and sugar beet are listed earlier.

VOLUNTEER CROPS AS WEEDS

Whilst traditional plant breeding methodologies have created diversity in some genera (e.g. high erucic rapeseed v '00' rapeseed, both being *B.napus*) the development of transgenic technology has enabled much wider diversity to become a realistic option; in *B.napus* this will lead to the introduction of a number of cultivars with specific fatty acid composition. In addition to double low and high erucic acid will be high oleic acid, high lauric acid, high stearic acid and, perhaps high petroselinic acid types. Similarly in the potato in addition to current cultivars will be high amylose, high amylopectin or specific pharmaceutical-producing types. Furthermore, other field crop species, for example sugar beet, are in various stages of transgenic development.

Unfortunately, some crop species have the propensity to produce large numbers of volunteer plants following harvest ; rapeseed and potato are excellent and contrasting examples.

Cussans (1989) anticipated at least 1% seed loss from combine harvested crops. In the author's view this amounts to at least 30kg/ha in a winter rapeseed crop, approximately 6 times a normal seedrate. Unpublished observation from ADAS High Mowthorpe (Perks - Personal communication) showed plants to develop from rapeseed initially harvested 10 years earlier.

In potato, residual populations of tubers ranging from 460,000 per ha in The Netherlands (Lumkes, 1974) to 370,000 per ha in UK (Lutman, 1977) have been reported.

Clearly in each instance there is a considerable opportunity for an ensuing crop of the same species grown later in the rotation to be contaminated to an unacceptable level by volunteers. Hence a well based strategy for controlling such volunteers needs to be produced and promulgated. To a degree this has been proposed for potatoes (Askew, 1991) and for rapeseed by Simpson (1993).

COSTS OF WEED CONTROL

As with existing crops weed control will be based upon a simple cost:benefit ratio. However the availability of agrochemicals and their pricing will be dependent upon the size of the potential market. In some instances markets would be exceedingly small. Perhaps therefore there will be limitations on availability of agrochemicals particularly where new industrial crop species are not related to existing crops, as proposed by Makepeace (1993) where it was suggested that a minimum crop area of 100,000 ha was needed to justify development of an agrochemical.

THE FUTURE

Ideally all industrial products should be derived from existing crop species. With transgenic capabilities there may be good opportunities to make progress in some species, for example, oilseed rape. However from the practical agricultural perspective minimisation of species on-farm will lead to a number of practical problems, which in UK at least, may be insurmountable. On that basis diversity of species will become an appealing option, provided that weed control systems can be developed to meet the needs of the specific crop and situation. Clearly in some instances that will not be a practicable proposition with agrochemicals alone.

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WEED CONTROL IN POTATOES, OILSEED RAPE, PULSES AND SUGAR BEET - TRENDS AND PROSPECTS

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ABSTRACT

Potatoes, oilseed rape, pulses and sugar beet are the major arable break crops grown in cereal rotations. This report provides a brief summary of the current status and future prospects for weed control within these crops. It is predicted that there will be some move towards more mechanical weed control in potatoes, but effects on crop quality will mean that this will only be used on certain soils. There has been a small reduction in the use of herbicides in winter oilseed rape since 1988, resulting from reduced control measures of broad-leaved weeds but an increased reliance on specific graminicides. Whilst new herbicide developments in potatoes, sugar beet and oilseed rape will help overcome some of the weed control problems in those crops, pulses could suffer a reduction in available treatments.

POTATOES

For many years the UK has enjoyed greater price stability of potatoes than elsewhere in Europe. Human consumption of potatoes in Great Britain is buoyant at 106.1 kg per head of population in 1993, 7.9 kg higher than ten years previously (Anon, 1994a). In the same ten years, the number of registered producers fell from 26499 to 16308, and the planted area from 165 to 148 thousand hectares. Potato yields have continued to rise, those of early varieties from 22.0 to 29.0 and main crops from 33.2 to 46.8 t/ha between 1983 and 1993. However, the abolition of the Potato Marketing Board in 1997 is causing some uncertainty and, whilst research interests may be protected in the future, the close control of production would seem to be coming to an end.

Husbandry changes and their effects on weed control practice

Light soils present the potato grower with fewer problems of husbandry and mechanisation than heavy soils, and the majority of the country's potato area is now concentrated on soils classified as no heavier than medium. Irrigation prior to crop defoliation reduces the risk of tuber vascular browning caused by some desiccants or sudden crop death. The effect of defoliants is useful for previously uncontrolled weeds such as *Polygonum aviculare* and *Chenopodium album* which can interfere considerably with harvesting.

Stone windrowing minimises damage on many light soils and reduces the adverse effects of clods on heavier soils. However, this limits options for weed control to chemical methods only. The technique of growing potatoes in beds has gained in popularity on light soils, but limits options for weed control. Flat topped beds are easier to cultivate than individual ridges, but can not be remade so easily.

Trends in herbicide usage

Herbicides were applied to approximately 266,000 ha of ware potatoes in England and Wales in 1992, and desiccants to 111,000 ha (Davis *et al.*, 1992). This represents 173 and 72% of the crop respectively and compares with 172,000 ha (124%) treated with herbicides and 70,000 ha (50%) treated with desiccants in 1988 (Davis *et al.*, 1988). In 1992, major usage was of paraquat and paraquat/diquat mixtures (55% of the crop), metribuzin (32%), linuron (23%), terbutryne/terbuthylazine (9%) and cyanazine (6.5%) with bentazone used on only 2.8%. Figures for 1988 do not allow exact comparison, but 33% of the crop was treated with paraquat, 28% metribuzin, 17% linuron and 18% monolinuron/paraquat. The figures show that many growers relied on sequential applications or mixtures. Varietal restrictions and a quite short application window restrict post-emergence spraying of broad-leaved weed herbicides. Specific grass weed herbicides were applied to approximately 1% of the crop in both 1988 and 1992, an indication that many growers rely on glyphosate pre-harvest or on the stubble of a preceding cereal crop to reduce perennial grass weed problems in advance of potatoes.

Sulphuric acid was used to desiccate 35% of the crop in 1992, and diquat 20%. Over 40% of the crop was left to senesce naturally or be defoliated mechanically, the other desiccants, metoxuron and glufosinate, being used on only a small area. Only 50% of the crop was desiccated in 1988. The increased use of sulphuric acid in 1992 suggests that growers are prepared to pay highly for rapid, safe and complete desiccation.

Weed control by cultivation

Potatoes were traditionally viewed as a cleaning crop, and regular, repeated cultivations generally reduced yields by 5% or more (Beveridge, *et al.*, 1964). Reduced cultivation techniques were introduced in the early 1960s and compared favourably with the herbicides that were becoming available (North & Proctor, 1966). The development of more effective herbicides and reducing labour forces encouraged growers to favour herbicides during the 1970s. More recently, environmental concerns and the need to examine variable costs have generated new interest in mechanical weed control, and new methods have proved capable of competing with the best herbicides currently available (Kilpatrick, 1993).

Problems faced by growers

The range of herbicides currently available is sufficient to meet the needs of most potato growers in seasons when the weather is favourable. Broad-leaved weeds may be difficult to control in very wet, dry or windy springs, because the relevant herbicides have a relatively narrow application window. Contact materials need weeds present but little or no crop, residuals need a settled ridge and moisture to activate them, and all need to be applied under low wind speeds to ensure even cover of both sides of the ridge. When these conditions can not be met, growers may be forced to rely on post-emergence herbicides or cultivations, but post-emergence sprays have varietal restrictions, and cultivations may not be a realistic option. The requirement is for another post-emergence product to complement metribuzin and bentazone.

Future prospects

New methods of mechanical weeding may appear attractive to the smaller grower on particularly weedy land, especially where a high organic matter content may limit his herbicide options. It remains to be seen whether the technique will be taken up by the larger grower but the requirements of a damage-free sample will govern his system.

New herbicides have been announced which can be applied post-emergence of the crop, thus offering possible solutions to the shortcomings in this sector. Prosulfocarb proved particularly effective against *Galium aparine* but controlled a range of other weeds when applied either alone or in mixture with metribuzin or metobromuron (Hemmen & Konradt, 1991). Rimsulfuron (DPX-E9636) controlled certain annual and perennial grass and broad-leaved weeds, and was equally safe on all varieties tested. Because of rapid degradation, no rotational or ploughing requirements were envisaged (Reinke & Rosenzweig, 1991).

OILSEED RAPE

The area of oilseed rape in England and Wales in 1992 was 419,757 ha compared with 304,144 ha in 1988 (Davis *et al.*, 1988; 1992). The area grown in future will depend partly on how the crop competes with other edible oilseeds, and partly on its development for use in industrial processes such as the manufacture of bio-diesel. Oilseed rape as a food crop is supported under the Arable Area Payment Scheme, but receives no support as an industrial crop. Due to a number of devaluations of the green pound, current returns from the supported area are much higher than expected when the scheme was introduced, but most growers have examined carefully their variable costs, and weed control appears to be a candidate for reduction.

Herbicide usage

Excluding desiccation, 181% of the oilseed rape crop was treated with herbicides in 1988 compared with 160% in 1992. The other main changes in herbicide usage between 1988 and 1992 were an increase from 49 to 63% of the crop sprayed with a specific graminicide, a reduction from 48 to 24% in the use of propyzamide, and an increase from 15 to 25% in the use of metazachlor. The use of clopyralid alone or with benazolin remained constant at about 26%, whilst the trifluralin and cyanazine-treated areas increased from 1.8 to 5.2% and from 2.4 to 3.9% respectively. The area of the crop desiccated pre-harvest remained almost constant at about 33% (Davis *et al.*, 1988; 1992). These figures suggest growers placed increased reliance on specific graminicides to control volunteer cereals and other grass weeds and did less to control broad-leaved weeds. The increase in the use of the cheaper herbicides, trifluralin and cyanazine, was small but significant.

The use of herbicides in the spring oilseed rape crop was not itemised separately by Davis. However, it is known that many growers rely solely on the rapid growth of the crop to smother broad-leaved weeds. Others use trifluralin, which may account partly for its increased use. Wild-oats are considered a greater threat to yield and are treated specifically where they occur.

Benefits from weed control

Experiments in the late 1970s and early 1980s showed inconsistent yield effects from the elimination of weeds by pre-drilling or pre-emergence compared with post-emergence herbicides in winter oilseed rape (eg Ward & Turner, 1985). Subsequent work in the mid 1980s suggested that the yield of winter oilseed rape was not significantly reduced by moderate levels of broad-leaved weeds in well-established crops (Bowerman, 1989). Experiments in the late 1980s indicated that broad-leaved weed problems were likely to be greater in less competitive crops of winter oilseed rape but, even at low seedrates, significant yield increases were not obtained (Sansome, 1989).

Competition experiments with winter barley in the mid 1980s confirmed earlier studies (eg Orson, 1984) which showed that vigorous crops could tolerate high populations of volunteer cereals without yield loss. Less vigorous crops, however, suffered large yield losses from barley infestations in excess of 100 plants/m². However, removal of even high infestations before December was shown to be unnecessary (Ogilvy, 1989). Economic weed control thresholds of 15 to 100 volunteer barley plants/m² were suggested by Lutman (1989) for later-sown or poorly established crops.

Weed control decisions should also consider the problems that weeds can cause at harvest, their effect on seed sample quality and the complications this may cause the crusher. Rapeseed should be regarded as the cleaning crop in a cereal rotation. *Bromus sterilis* and *Alopecurus myosuroides*, for example, can be killed with a single well-timed application of propyzamide, but use of this herbicide is declining. Use of carbetamide, which offers similar advantages without being so persistent in the soil, has declined much more. The increasing use of specific graminicides to which strains of *A. myosuroides* are becoming resistant is an ill-advised policy from the point of view of the whole rotation.

Future prospects

With cleavers being the weed that many growers find difficult to eliminate, and no product presently offering totally reliable control, the introduction of quinmerac is awaited eagerly (Lainsbury & Cornford, 1995). It is expected that it will be formulated with metazachlor, however, and whilst this appears to be a useful formulation, a good technical case can be made for it to be marketed as an individual chemical.

Looking further into the future, weed control in oilseed rape could become greatly simplified by the introduction of varieties genetically modified to resist herbicides such as glufosinate or glyphosate or the HBNs. Breeding programmes for spring varieties are in advance of those for the winter crop, so this could give a further boost to the spring-sown area. However, the principle of genetic modification remains to be fully accepted by both growers and the general public. When such varieties are introduced, oilseed rape will again stake its claim as the cleaning crop in a cereal rotation, but control of modified volunteer rape plants elsewhere in the rotation will need to be planned carefully.

PULSES

The area of protein crops grown after 1995 will depend on profitability relative to cereals. In 1993 the EU support system for peas or beans grown for protein for animal feed changed to an area payment which was set for a three year period. Profitability relative to cereals has decreased. Area payments for protein crops has increased from £365.66/ha in 1993 to only £388.79/ha in 1995, compared to an increase from £140.64 to £269.16/ha for cereals in the same period. World market prices, possibly £110/t for peas and beans in 1995 are much lower than 1992 when an EU subsidy was paid/t. Yield responses required to cover the costs of inputs such as weed control need to be managed with care (Knott, 1994). Yield increases when weeds are removed in herbicide experiments can be compared with 'break even' responses and used to make decisions aiming at the optimum financial return. Other factors such as the effect of weeds on harvesting and prevention of return of weed seeds particularly *Avena fatua* and, in beans, *G. aparine* are also important.

Beans

Winter beans are well suited to the UK climate and the area is higher than elsewhere in the EU. They are grown mainly on heavy clay soils and most are established by ploughing the seed down. The seedbeds often remain cloddy, thus weed numbers are low and the crop is competitive. Simazine, a cheap herbicide, is used on most of the crop either pre-emergence or in spring after levelling cultivations that remove weeds which have germinated. Spring beans are grown on a wide range of soils and most are drilled. Simazine is sometimes used but unless the crop is sown at adequate depth (70 mm) there is a risk of damage. There is a wide choice of residual pre-emergence alternatives. Surveys show that pre-emergence herbicides for broad-leaved weeds were used on 81% of the (winter & spring) field bean crop in 1994 (Anon, 1994c) and the situation has not changed over the years. Bentazone is the only herbicide registered for post-emergence use. It is relatively expensive and has a limited weed spectrum but about 8% of the crop is treated usually to control *G. aparine*, volunteer oilseed rape and *Fallopia convolvulus*. 'Hormone' post-emergence herbicides are too damaging for use in field beans and thus there are no opportunities to suppress *Cirsium arvense*.

Peas

There are more herbicide options for spring peas and, in contrast to beans, there have been changes in weed management. Rainfall following pre-emergence applications to early sown peas is usually adequate for good residual herbicide activity (although 1995 was an exception). Data from Produce Studies Ltd show that in 1983, 73.5% of the pea crop (dry harvest and vining peas) were treated pre-emergence and 25.2% post-emergence but in 1994 59.7% were treated pre- and 50.8% post-emergence. This trend is probably due to increasing infestations with volunteer oilseed rape which is inadequately controlled by many residual herbicides. Although certain other species such as *Poa annua* and *P. aviculare* are not controlled post-emergence and there is increased yield benefit from early removal of broad-leaved weeds (Knott, 1994), the cost of a pre- and post- programme is unacceptable to many farmers.

Specific weed problems in peas and beans

Grass weeds in peas and beans are usually controlled with post-emergence graminicides and, since these became available, there has been a trend away from pre-emergence and pre-sowing treatments. However, cost of the high dose required (£85 to £105/ha), means it is no longer economic to treat *Elymus repens* in the growing crop. Peas and field beans generally follow cereals in the rotation and since the UK ban on straw burning there has been a noticeable increase in volunteer cereals. Cost of control can be reduced by early applications provided all weeds have emerged. Recent experiments at PGRO showed that early removal of barley with a graminicide when peas were at 2-3 node growth stage or spring field beans at 2-3 leaf pairs, prevented yield loss, but applications four weeks later were uneconomic for peas and only worthwhile in beans for the highest grass weed populations.

Although volunteer oilseed rape can be controlled in peas and beans, volunteer potatoes remain a long term intractable problem. Volunteer potatoes are increasing in pea and bean crops for processing (Knott, 1993). There are opportunities for rotational control of volunteer rape and potatoes but these are seldom planned on the farm and control within growing pulses is unlikely in the near future, if at all. Herbicide resistant potato and oilseed rape volunteers could have severe consequences for the pea and bean grower (Lawson, 1993).

Crop and cultivar trends

Sweet lupins have nutritional advantages as an animal feedstuff and are eligible for EU area subsidy. In autumn 1994 approximately 100 ha were sown but poor competitiveness at early stages of growth and lack of tolerance to most post-emergence herbicides are major problems.

The winter pea area could increase, particularly where drought stress during flowering affects spring sown peas and in the north where earlier harvesting is useful. The newer winter hardy French cultivars are semi-leafless, but produce several tillers and suppress weeds. Autumn germinating *G. aparine* cannot be controlled with current herbicides and is a limiting factor on some farms.

Most peas grown are now semi-leafless cultivars, with improved standing ability, and the desire for earlier maturity led to many winter and spring bean cultivars with shorter straw. All of these are less competitive with weeds than the older cultivars they replace.

Effect of reduced inputs in other crops in the rotation and set-aside

Reduced inputs, including herbicides in cereals may increase weed pressures in crops such as pulses, and some researchers (Wright *et al.*, 1993) have warned of this. Most of the data on yield response to weed removal with herbicides were generated in relatively 'clean' fields. In rotational set-aside there is now an opportunity to control annual and perennial grasses (with permission from MAFF) and hence scope for reduction of herbicides in following crops.

Future prospects

Increased costs of maintaining registrations for agrochemicals will result in loss of active ingredients for minor crops such as peas and beans. EU reviews of active ingredients may have implications. For example, although 50% of the UK crop was treated with MCPB alone or in formulation in 1994 (Anon, 1994c), it is not widely used elsewhere and generation of new data to support this use may not be economically worthwhile. Some of the triazines, which form the basis of all residual herbicides for peas and beans, may also fall into this category. Environmental demands may also have an effect. Withdrawal of simazine would increase costs of weed control in field beans from £7/ha to £40/ha.

One new active ingredient, fomesafen (a soya herbicide) was registered in the UK specifically for peas and beans in 1994, but this is an exception and, although there may be other possibilities, their development is unlikely and this is discussed by Ryan & Gutbrod, 1991.

Mechanical weeding is not a cost-effective alternative to herbicide use. Species with a strong rooting system (eg *Sinapis arvensis* and oilseed rape volunteers) are not removed with flexible tine weeders and costs and control levels are unacceptable (Knott, 1994). Dose manipulation is becoming popular in peas, but requires expert knowledge and precision timing. However, there are some prospects for control of small oilseed rape volunteers, at cotyledon to 2 true leaves stage, with an early application of a half dose of bentazone/MCPB plus cyanazine.

SUGAR BEET

The area of sugar beet grown in the UK is governed by EU quota and is around 175,000 ha. Some reductions can be expected as quotas are reduced. Weed control has always been recognised as an important part of sugar beet husbandry (Achard, 1799). The critical periods for weed control have been defined by various workers (eg Scott *et al.*, 1979). It is usually accepted as between emergence and six to eight true leaf stage of the beet. Weeds emerging after this stage are not expected to compete with the crop. Competition is for moisture and nutrients when these are limiting, but that for light is always important. Therefore tall growing weeds which shade the beet from sunlight can cause substantial yield losses (Schäufele, 1986). As few as one *C. album*/m^2 can reduce sugar yields by 1% and this effect was also observed for weed beet by Longden (1989). Modern beet varieties are diploid with an upright habit compared to the triploids they replaced. Diploid crops are poor at suppressing late germinating weeds (Lotz *et al.*, 1991).

The major weeds of sugar beet worldwide are *E. repens*, *C. album*, *F. convolvulus*, and these are important weeds in the UK and northern Europe. These can be controlled with appropriate herbicide programmes. The main problem weeds that are difficult or expensive to control in the UK are *Aethusa cynapium*, *C. arvense*, *Solanum tuberosum* with *P. aviculare*, *Polygonum persicaria*, *Polygonum lapathifolium* and *S. arvensis* difficult under certain growing conditions.

Current weed control practices

Weed control systems for sugar beet in each country or area are governed by local growing conditions, weed species, politics and farm structures. Since the 1980s the majority of farmers in the UK have used a low volume, low dose system of weed control (Smith, 1983). Whilst the row formation of sugar beet offers the opportunity to use band spray and tractor hoe systems, approximately 5% of the UK area is so treated (Anon, 1994b). The reason for this is the high labour requirement for tractor hoe systems, despite the use of guidance systems and fast forward speeds (McClean & May, 1986).

In the UK, the average sugar beet field receives a three-spray herbicide programme (Anon, 1994b). Approximately 66% of the beet area receives a pre-emergence residual herbicide as part of the programme. Chloridazon is the most popular herbicide (27% of the 66%). Post-emergence herbicides are largely based upon mixtures and sequences of phenmedipham, metamitron, ethofumesate and lenacil with clopyralid included for control of weeds such as volunteer potatoes (*S. tuberosum*), *C. arvense* and *A. cynapium*. Since 1994, desmedipham has partially replaced phenmedipham in some mixtures. Grass weeds are controlled by the use of specific graminicides such as fluazifop-p-butyl, cycloxydim, quizalofop-ethyl and propaquizafop. Apart from the introduction of desmedipham in 1994, the use of herbicides has changed little in recent years (Anon, 1990, 1991, 1992, 1993), any differences between years reflecting changes in season rather than any other factor.

The future

The future may see changes in use in the UK with the advent of a number of new herbicides within the next five years (Morley had five new active ingredients for sugar beet under test in 1995). The first to reach the market will be triflusulfuron and this may change the ratios of products and the total ai used for weed control in the crop (Fisher *et al.*, 1995). The other change will occur around the turn of the century with the introduction of herbicide (glufosinate or glyphosate) resistant beet. The general trend with all new herbicide programmes is a reduction in the amount of residual herbicide used post-emergence. Late germinating weeds such as *C. album*, *Solanum nigrum* and, in certain locations, *Amaranthus retroflexus* will become major problems. In addition, timing may be more critical in order to get the optimum use of contact or foliar activity. Lower dose systems (May & Cleal, 1993) are finding favour with some growers, but they require extra spray passes across the crop and reduced farm labour forces may not be able to cope.

The major factors deciding whether mechanical systems will partially or totally replace herbicides will be political (as in Scandinavia where reductions in herbicide use are leading to developments in mechanical control) and/or costs. At present in the UK, the costs of mechanical systems in both time and money mean that overall herbicide applications are likely to be the norm rather than the more labour intensive band spray/tractor hoe systems. Overall weeders may offer a partial solution, but will need to be used with appropriately adjusted herbicide programmes.

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