Session 6B

Targeted Inputs for a Better Rural Environment

Chairman	Professor S Hughes
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NEW TECHNOLOGY FOR ENVIRONMENTAL BENEFITS: OPPORTUNITIES FOR INDUSTRY.

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ABSTRACT

The difficulties of persuading farmers to take up integrated and organic farming systems are analysed and an alternative approach is described which focuses on the potential of new technology (from chemicals, biotechnology, IT and engineering developments) to improve the environmental performance of intensive arable systems. The opportunities presented for industry by this approach and the policies required to implement it are discussed.

INTRODUCTION

Various approaches have been proposed over the years for reducing the environmental impact of intensive agricultural systems. They are generally based on the assumption that environmental impacts will be lessened if the usage of potentially damaging inputs is reduced or eliminated, if they are replaced by less damaging products or if they are applied more accurately. Two related trends can be identified in most of the approaches proposed so far to deal with these problems.

- Organic. The first is to avoid the use of artificial chemical inputs altogether through the adoption of organic systems of production using fertilisers of natural origin based on animal manure or plant residues, encouraging pest and disease control through the use of natural enemies and using cultivations to control weed problems. Technological inputs from the engineering or IT sectors are accepted as part of organic systems, but not the products of the chemical or biotechnology industries.
- Integrated. The second is to move to integrated farming systems which focus on managerial aspects of farming, such as crop monitoring, crop rotation, mechanical cultivation and more accurate timing of inputs, in order to maximise the role of natural ecological support systems in crop production. Farmers operating integrated systems do, however, accept the use of chemical and biotechnological inputs where required to maintain yields, in addition to engineering and IT-related inputs.

Some farmers have been willing to move to organic and integrated systems, often for reasons of 'lifestyle' in that they view modern intensive systems as unsustainable and environmentally damaging (Pretty & Howes, 1993, p7). A perceived need to reduce costs in the face of reforms to the CAP and declining farm incomes up to 1993 has led in some cases to a reduction in levels of inputs (Jordan & Hutcheon, 1994, Ogilvy *et al*, 1994) which is often somewhat uncoordinated and should not be regarded as the uptake of integrated systems in the strict sense of the words. The 1992 Common Agricultural Policy (CAP) arable reforms also seem to have resulted in a slight reduction in inputs to arable land, but mainly as a result of a decline in the cropped area, the situation being complicated by the recent increase in farm incomes, boosted by the rise in world cereal prices and favourable exchange rates (Rayment, 1995).

For various reasons, most farmers have not yet taken up organic and integrated systems, including the largest and most intensive farmers. Organic systems are unattractive because of the difficulty of running an organic cropping system without a livestock enterprise (Murphy, 1992). The current reliance on a price premium for organic produce is seen as unsustainable in the event of a move of larger numbers of farmers to organic production (Pretty & Howes, 1993, p15). In addition, such a radical change in the nature of the farming system would require a new range of managerial skills on the part of the farmer and would in many cases result in a period of significantly lower yields, at least during the transition phase (Lampkin, 1990).

Integrated farming systems are presented by their proponents as a sustainable alternative to organic farming and also as being more attractive to farmers. The financial results on integrated farms, in terms of gross margin, are often comparable to those from conventional farming systems, any reductions in yield being compensated for by a corresponding reduction in the cost of inputs. Pretty & Howes (1993, p(i)) have estimated that integrated farms can match or better the gross margins of conventional farming, although there is usually a yield per hectare reduction of 5-10% for crops and 10-20% for livestock. However, this in itself does not create an incentive to take up such systems, and the analyses which show comparable levels of profitability between integrated and conventional systems have not allowed for the considerably increased inputs of managerial and knowledge skills and of labour required by integrated systems (Ogilvie *et al.*, 1994, Jordan & Hutcheon, 1994).

For such reasons, a high proportion of the intensive farming community is unlikely voluntarily to take up integrated or organic farming systems and these farmers account for a very significant proportion of the total impact of agriculture on the natural environment. Based on previous experience, farmers in this category are only likely to undertake such a radical revision of their current practices where the use of fertiliser and pesticide inputs has undermined the natural ecological support systems for agriculture to such an extent that that it becomes impossible to grow particular crops or where they are legally required to do so. Given the continually increasing trends in yield/ha of the major arable crops in the UK (e.g. Orson, 1995), it is difficult to convince farmers that their current practices are unsustainable, at least from the agricultural perspective. There is therefore no reason to expect a major switch from intensive farming to the integrated or organic systems which could deliver environmental benefits. Given these constraints, Scottish Natural Heritage (SNH) has set up an initiative to explore a different approach to the environmental problems associated with intensive farming. The TIBRE Project (Targeted Inputs for a Better Rural Environment) explores the potential of new technology to reduce the impact of farming on the environment.

THE ROLE OF SCOTTISH NATURAL HERITAGE

SNH was established under the Natural Heritage (Scotland) Act 1991 to conserve and enhance the natural heritage of Scotland and to further its understanding and facilitate its enjoyment, combining the functions of the previous Nature Conservancy Council and Countryside Commission for Scotland. It is required to have regard to the desirability of securing that anything done in relation to the natural heritage of Scotland is undertaken in a 'manner which is sustainable'. SNH therefore has a duty to consider the natural heritage as a whole, including the full range of farm types, from crofting and hill farming in the north and west to the more intensive animal and arable farms in the south west and south east. Support is given to work on the management of organic and integrated farms. Across all types of farm, support is also given (along with other partners) for habitat creation and management, particularly hedgerows and other field margins, small woodlands and ponds. However, on many intensively managed farms, we are aware that these peripheral areas are less productive and diverse as wildlife habitat than they might be because of the environmental impacts arising from farming activities on the cropped areas (Cooke & Burn, 1995).

A comprehensive approach to conserving the natural heritage of farmed land therefore has two strands. One is to provide for the management of existing wildlife habitats and landscape features and, where the opportunity arises, to create new ones. The other, which provides the justification for TIBRE, is to protect these habitats and features from the potentially harmful effects of agriculture. The aims of the TIBRE initiative are:

- to improve the environmental sustainability of agricultural systems through the uptake of new technology;
- to reduce the environmental impacts of intensive agriculture on productive areas of farms and to minimise the impact on the surrounding non-farmed wildlife habitats;
- to encourage commercial companies to speed up the development of new technology with improved environmental performance and with an equal or greater agronomic performance;
- to influence policy so as to foster appropriate technological innovation; and
- to foster the development and adoption of appropriate technology by working with relevant partners in the UK and in other EU countries.

The TIBRE focus on new technology with the potential for environmental benefits is, so far as we are aware, unique among organisations concerned with nature and landscape conservation, at least in the UK. The assumption, implicitly or explicitly, in most of the references quoted above is that a move to integrated or organic systems is the only way to achieve the greater sustainability in agricultural systems, to which the UK Government has now made a commitment (Anon, 1994). The TIBRE project was set up to explore the role of new technology in achieving the required levels of overall sustainability without bringing in the problematic management, labour and other costs associated with organic and integrated systems, which inhibit their uptake by farmers.

Although intensive agriculture is the major area of interest for TIBRE, the technological developments which this approach aims to encourage also have the potential to give added environmental benefits in integrated systems (see Figure 1).

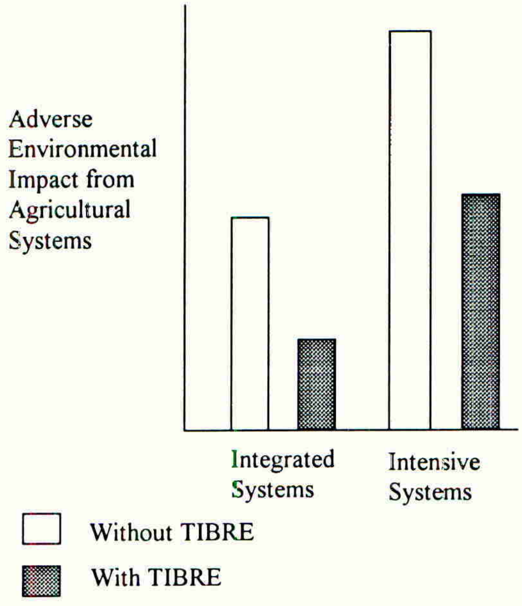
TECHNOLOGICAL INNOVATIONS FOR ENVIRONMENTAL BENEFIT

The following programme of work on TIBRE has been undertaken by SNH over the past two years.

Initial consultation

SNH undertook a preliminary consultation in order to gauge the reaction of a wide range of stakeholders to the proposed TIBRE project, to indicate how the project might be developed and to investigate the extent of any other work in this area. The proposal was circulated to research institutes, universities, voluntary bodies, agrochemical companies, the National Farmers' Union of Scotland (NFUS) and the Scottish Office Agriculture and Fisheries Department (SOAFD). The proposal was also discussed with the European Commission (DGVI and DGXII) and the Organisation for Economic Co-operation and Development (OECD) in Paris. There was general support for the idea, particularly from farmers, farming organisations, agricultural researchers and the agrochemical industry. Reservations were expressed by some voluntary nature conservation bodies who placed more emphasis on the need to encourage environmentally sensitive farming by traditional methods in areas which are already rich in wildlife.

Figure 1. Environmental Benefits from TIBRE



Option appraisal

Surveys of relevant technological developments, recently on the market, soon to be available or in the early stages of research and development, were commissioned in the areas of chemical technology, biotechnology, information technology, and agricultural engineering. Details of the option appraisal will be published elsewhere.

Inter-agency working group

A working group was set up, involving the research community, farming advisers and consultants, the agrochemical industry, policy makers and voluntary conservation organisations. These were seen as bodies which would have a crucial role to play in implementing the ideas and proposals developed under the TIBRE initiative. The advice from the first meeting of this working group helped SNH to take forward the options identified by the initial surveys and to set up the consultation with farmers. Further meetings will be convened to consult the working group on the longer term aspects of the implementation of TIBRE in the UK and in the wider international context.

Technology assessment

The developments identified by the option appraisal were evaluated for their potential influence on the natural heritage, based on: a reduction in the load of a known toxin; substitution of a safer alternative; protection of ground or surface waters; protection of natural habitats; protection of the soil resource, e.g. through reducing nutrient load; and reduction in gaseous nitrogen loss. The assessment considered the availability of innovations, economic and agricultural factors likely to influence farmers' attitudes, and the possibilities for synergistic interactions among existing and new developments.

Some options are already available on the market but have not been taken up by many farmers. Others will soon be available. In these cases, SNH will consider how farmers could be encouraged to adopt them. We are also aware that many potentially beneficial innovations are not taken beyond the early stages of research and development because the companies involved do not see a viable market niche. Because of commercial confidentiality it is difficult to obtain information on the nature and possible numbers of such products. However, in these cases the TIBRE project could contribute to the creation of a favourable commercial climate which would encourage companies to see environmental benefits as a strong selling point for new technological developments.

Economic and agricultural factors likely to influence farmers' attitudes to new technology included the economics of adopting and using a product, the degree to which it disrupts current management of the farm or inconveniences the farmer, changes in financial risk and the requirement for supporting technical advice. Because of their importance in influencing farmers' attitudes, such factors were given a high weighting in the evaluation of options.

Synergistic interactions among new developments could arise where products have an enhanced environmental effect if they are incorporated as mutually supportive parts of a system. This applies particularly to information technology and agricultural engineering developments such as global positioning systems, yield mapping and decision support systems, which could be combined with the use of more selective, lower dose products to give an enhanced environmental benefit.

Overall the assessment showed that many products and technologies, some of which are already available on the market, had the potential to offer a direct or indirect advantage over conventional intensive agricultural production. The next stage of the TIBRE project was to discuss this list of options with the farmers themselves.

Farmer consultation

A two-day workshop was held with twenty arable farmers who occupy an influential position in the farming community and who are motivated to a high degree by business concerns. Some were known also to have an interest in the environment but this was not a factor in the choice. Those options which had been proposed by the technology assessment as potentially useful were ranked by the farmers on the basis of perceived value to them. The results of this assessment will also be reported elsewhere.

In general farmers strongly appreciated their involvement in the development of this project at an early stage in our thinking and wished to remain involved in future. The TIBRE approach was seen as a valuable input to thinking on policy and practice and many farmers felt that there was a lack of information on the potential environmental benefits of new technology.

INDUSTRY OPPORTUNITIES AND POLICY PERSPECTIVES

The first phase of the TIBRE project has examined the potential of new technology to deliver environmental benefits, and the acceptability of the TIBRE approach to farmers and other stakeholders, largely from a Scottish perspective. Having prepared the ground carefully, we are now in a good position to encourage the uptake of relevant technology which is currently available in Scotland, in close partnership with farmers and their advisers.

The longer term aims of TIBRE are to encourage companies to give greater emphasis to the development of new technology with improved environmental performance and to influence policy so as to foster appropriate technological innovation. This has already happened to some extent, for example through the steady improvement in the ratio of application rate to LD50 in more recently developed herbicides (Davies, 1995). However, these aims need to be taken forward in a more focused manner, at least at a European level. In the research and development process in multinational companies, a new chemical or biotechnology product will need to have a large projected international market in order to recoup its R&D costs. This is less true of developments in engineering and IT, but they also must be compatible with existing farming systems which are dependent on the outputs of the multinational companies.

On the policy side, there is often an assumption that agricultural surpluses will continue to be a potential problem for the foreseeable future (e.g.Jordan & Hutcheon, 1994).

However, various factors could alter this situation. Short-term climatic fluctuations or longer-term climate change could lead to major shortfalls in food production in some areas, creating pressures to increase production in others. Competing uses for agricultural land for fuel and fibre production could increase the pressure to maximise productivity on land which remains in food production. New biotechnology developments could lead, within the next five years, to the ability to grow specific proteins for drugs, vaccines and other high-priced outlets (Hillman & Wilson, 1995) giving a considerably greater gross margin than food crops. If taken up on a large scale this would displace food production onto lower quality land, where it may require a greater use of inputs to maintain yields. If we see a return to maximum food production based on existing technology, the environmental impact of agriculture could begin to increase again. A more robust environmental policy for intensive agriculture, in the face of these potential changes, would be to encourage the development of new, environmentally sustainable technology now, so that it is available when needed in future (Tait & Pitkin, 1995). However, it is important also to be aware of a range of government policies and other pressures which are relevant to this issue and which are not necessarily compatible with one another - including industrial and agricultural support policies, regulatory policies and public opinion.

Industrial support policies

Since the mid 1980s, there have been concerns in the agrochemical industry about its ability to remain in the high-tech, high value-added sector of the economy and to avoid a decline to become a purveyor of commodity products. Biotechnology seemed to promise a new generation of innovations which would prevent this slide in the status of the industry (Fernandez, 1985) and would enable it to continue to expand in a more environmentally acceptable manner. However, the rate of innovation for agriculture has proved slow in comparison to the pharmaceutical sector, largely because of the depressed state of the market in the farming community, compounded by uncertainty in industry about levels of regulation, patent law and public opinion, and about the reduction in state support for near-market development and advisory services (Tait, 1993). Other areas of innovation for agriculture, such as engineering and IT, have been similarly sluggish until recently. Under these pressures, many products with a potential to deliver environmental benefits have been rejected by companies at an early stage in the R&D process.

Increased recognition is now being given by governments to the need for specific support mechanisms to encourage technological innovation and to foster international competitiveness. Examples are the EU Fourth Framework Programme and the UK Technology Foresight Initiative. In the latter context, the report dealing with agriculture, natural resources and the environment refers to the potential of industries in this area to deliver wealth creation, a better quality of life and greater sustainability (Hillman, 1995). Such initiatives will help to stimulate the type of development needed for inclusion in projects like TIBRE.

Agricultural support policies

The recent General Agreement on Tariffs and Trade (GATT) agreement and the EU CAP reforms have removed controls on prices and production to encourage a convergence between European and world commodity prices. One predicted effect of these changes is a reduction in the variety of agrochemical products available to European farmers (Fidgett, 1994). At the farm level, the effect of these changes may be to encourage a greater use of inputs as an insurance policy against market risks, with an emphasis on cheaper inputs which are less environmentally benign. The justification for agricultural support has shifted away from the encouragement of food production and technological development towards rural development in disadvantaged areas and also towards specific environmental objectives such as the preservation of species and habitats (CAP Review Group, 1995). The trend in this policy area is therefore in a direction which would make it increasingly difficult for policy to focus on the encouragement of environmental benefits from new technology, as proposed by TIBRE.

Regulatory policies

Many people in industry have a negative view of regulation and regard it as inhibiting the process of innovation. There are also government moves, particularly in the United States, for wholesale 'deregulation', at a time when the public appears to want stricter regulation (Rose, 1995). While unnecessary regulation is wasteful of resources, the UK government has recognised that, without regulation, market inefficiencies will occur and that regulation may be required, for example to discourage pollution and the abuse or misuse of agrochemicals (CAP Review Group, 1995). Industry managers are gradually becoming more aware of the potential of regulation to create new markets for innovative products that would otherwise be unable to compete with cheaper, off patent and often more environmentally damaging products. It is also important to note that a strong regulatory system helps to reinforce public trust in an industry sector and to create a more favourable marketing climate for its products. If we are to achieve the economic and quality-of-life benefits from initiatives like Technology Foresight, it is important to avoid a dogmatic response to regulatory issues.

Public opinion

In our discussions with farmers involved in the TIBRE project, they were very concerned about the public image of intensive farming systems. The agrochemical industry itself has also had a series of public information campaigns intended to improve its image, with only partial success. These public concerns have recently spread to new biotechnology, an area where many developments could prove environmentally beneficial compared to traditional alternatives. In a survey of public attitudes to biotechnology (Martin & Tait, 1993) many respondents felt that it was unacceptable for industry to focus solely on the profit motive in developing new technology and were against biotechnology because the products coming forward did not seem to be satisfying any public need such as a reduction in the environmental impact of agricultural systems. A project based on TIBRE could be influential in improving public perceptions of agriculture-related industries at least as regards environmentally beneficial technology, and could perhaps encourage a more rational response to more neutral technologies.

CONCLUSIONS

Within SNH, TIBRE is one of a suite of policies dealing with the whole range of agricultural systems, from crofting and hill farming to intensive arable cropping. The initiative is targeted towards those intensive farmers who are unlikely, for a variety of reasons to take up organic or integrated approaches as a means of reducing the environmental impact of their operations. As indicated above, there are significant opportunities in this approach, for industry, farmers and the environment. However, the policy environment is not uniformly favourable to it. TIBRE is potentially very compatible with the more liberal trading climate ushered in by recent policy reforms. It also has the potential itself to form the basis of a more robust policy for environmental protection in light of these reforms and of new, competing uses for agricultural land. Policies which favour the implementation of TIBRE are already in place in the area of technological innovation. However, the direction being taken by some agricultural policies could act as a disincentive to the adoption of relevant new technology. A more co-ordinated and flexible approach to agricultural policies is required, which does not contradict the new policy initiatives, but which also allows new technology to help in their achievement and at the same time to contribute to wealth creation and to our quality of life. SNH would favour such an approach in the UK and more widely in the EU and would be prepared to work in partnership with others to foster it.

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THE ENVIRONMENTAL IMPACT OF HERBICIDES USED IN INTENSIVE FARMING SYSTEMS

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ABSTRACT

The environmental effects of herbicides are reviewed. Many different products are sprayed widely onto crops and there is evidence for a range of effects especially within cropped areas. The potential importance of indirect effects is also becoming apparent. Because of the complexity of factors operating in the field and the subtlety or inconspicuous nature of effects, proof of damage is still sometimes lacking. Nevertheless, the existence of problems should be appreciated, and remedial action should be considered and undertaken where feasible.

INTRODUCTION

Herbicides are important tools for managers of land of different types. Even conservationists use herbicides but relatively few products are applied to reserve areas; they are used infrequently and are usually applied in a precise fashion eg by weed wiper (Cooke, 1991). The aim of the conservationist is almost invariably to control one or a few invasive plant species while trying to ensure that the rest of the ecosystem is unaffected, at least directly. In contrast the aim of crop protection is to control a weed problem and so long as the crop species is unaffected, any additional effects may be regarded as of little agronomic consequence. In intensive farming systems a large range of herbicides is available; annual use in the UK can amount to more than a million hectares for a single product and virtually all is applied by ground sprayer. Consequently there is considerable potential for environmental effects both within and outside cropped areas.

In this paper we review the environmental effects of herbicides used in intensive farming systems, primarily arable agriculture. Freemark & Boutin (1995) in a recent review on effects on temperate, terrestrial wildlife pointed out that most of the evidence originated from the UK. We have, therefore, tended to concentrate on UK sources. Because of the constraints of space we have been selective in our use of references and we have not considered effects on micro-organisms.

DIRECT EFFECTS IN CROPPED AREAS

Within cropped areas there has not surprisingly been a major effect on native flora. Wilson & Sotherton (1994) have produced a guide to the conservation of 16 species of rare arable flowers, 11 of which were included in a recent project to update the British distributions of nationally scarce species (Table 1, Stewart *et al.*, 1994). Of the remaining 5 species, at least one, the pheasant's-eye (*Adonis annua*) is sufficiently endangered to be a Red Data Book species (Stewart *et al.*, 1994). Species that qualify to be regarded as "scarce" are found in 16-100 ten km squares and this classification applied to 5 of the species listed in Table 1. For one species, the mousetail (*Myosurus minimus*), there was no mention in the text of herbicides specifically being involved in any decline. For the other 10 species, herbicide use since the 1950s was considered to be implicated in the declines although other factors were also mentioned, especially the introduction of seed screening, use of fertilisers and low ability to compete with heavily-fertilised modern crop varieties. The fact that increased use of herbicides is only one of several factors that have changed considerably in recent decades has complicated our task of teasing out herbicide impacts. Cousens *et al.* (1988) highlighted the problems inherent in trying to determine whether native plants had been affected by herbicides. In an experiment over 36 years, while regular treatment with 2, 4 -D affected the relative abundance of plant species, it did not affect the list of species present (Hume, 1987). Fryer & Chancellor (1970) concluded that the major effect of herbicide usage in arable fields had been to reduce rather than eliminate weed populations. They also pointed out that many of the more tolerant dicotyledonous annuals were as frequent as ever at that time eg common chickweed (*Stellaria media*) and fat-hen (*Chenopodium album*). But a significant contribution of herbicides to the decline of the scarcer species can be in little doubt especially as some species are still regarded as weeds and are controlled by a range of modern herbicides at field rates (Table 1 and Wilson, 1991).

Table 1 Status of rare arable plants, the role of herbicides in their decline (Stewart *et al.*, 1994) and weed status (Flint, 1987).

Species	Status	Herbicides implicated in decline	Listed as weed species
Cornflower *Centaurea cyanus*	Scarce	✓	✓
Broad-leaved spurge *Euphorbia platyphyllos*	Scarce	✓	
Red hemp-nettle *Galeopsis angustifolium*	Scarce	✓	
Mousetail *Myosurus minimus*	Not scarce		
Prickly poppy *Papaver argemone*	Not scarce	✓	
Rough poppy *Papaver hybridum*	Not scarce	✓	
Corn buttercup *Ranunculus arvensis*	Not scarce	✓	✓
Shepherd's-needle *Scandix pecten-veneris*	Scarce	✓	✓
Night-flowering catchfly *Silene noctiflora*	Not scarce	✓	✓
Spreading hedge-parsley *Torilis arvensis*	Scarce	✓	
Narrow-fruited cornsalad *Valerianella dentata*	Not scarce	✓	

Another piece of evidence implicating herbicides in the declines of these species is that around the mid 1980s, Game Conservancy staff noted that reduced and modified herbicide use in "Conservation Headlands" in cereal fields promoted the re-emergence of rare species (Wilson & Sotherton, 1994). These authors provided practical suggestions for conserving rare arable species. However, many conservationists are reluctant to give priority to the conservation of species (once) regarded as weeds that are typical of such an artificial habitat (Stewart *et al.*, 1994). Nevertheless, it is not clear to us that all of the species in Table 1 were regarded as agricultural weeds, and encouraging them in conservation headlands will help promote biodiversity on farmland while not allowing these species to become serious pests. It should also be pointed out that the declining species have been replaced by more modern weeds such as black grass (*Alopecurus myosuroides*) and cleavers (*Galium aparine*) which are resistant to herbicides or can flourish on high inputs of nutrients (Stewart *et al.*, 1994).

As regards fauna, lethal and sublethal effects of herbicides used at field rates have been demonstrated in earthworms (Tomlin, 1992, Edwards & Stafford, 1978). Testing carried out by the International Organisation for Biological Control under laboratory, semi-field and field conditions has indicated the potential for direct toxic effects of herbicides on a range of beneficial arthropods, whilst in a review of laboratory test results for 77 pesticides (Klingauf, 1988), 54% of herbicides were classed as harmful or moderately harmful to several species of beneficial arthropod. Direct effects of herbicides on other groups of invertebrates have been tested less frequently. Sotherton (1982) showed that 2, 4-D was directly toxic to the immature stages of the chrysomelid beetle *Gastrophysa polygoni* under field conditions. In a study of effects on soil fauna of a range of herbicides, Edwards (1970) concluded that whilst toxic effects could be shown on enchytraeid worms, Collembola and mites, the direct effects on their populations were probably small relative to the indirect effects. However he cautioned the need for continued vigilance over direct effects on soil invertebrates.

Reports of the Wildlife Incident Investigation Scheme for 1990-1993 show a total of 70 incidents implicating herbicides. Many of these incidents involved deliberate abuse aimed at poisoning vertebrate wildlife or companion animals. Definite examples of incidents stemming from approved use are rare eg the death of a brown hare (*Lepus europaeus*) from paraquat poisoning in 1991; paraquat had been linked comparatively frequently with hare deaths, but the picture was complicated by the occurrence of a virus specific to hares (Fletcher *et al.*, 1991). Paraquat formulations carry the warning, "may be harmful to hares, where possible spray stubbles early in the day". One of the best publicised incidents in recent years occurred in Kent in 1990, when sodium monochloroacetate sprayed in an approved manner on an onion field poisoned large numbers of passerine birds (Greig-Smith *et al.*, 1990); drinking from puddles was suggested as the exposure route. Occasionally honey bees (*Apis mellifera*) have been poisoned by herbicides (Greig-Smith *et al.*, 1994).

INDIRECT EFFECTS IN CROPPED AREAS

The indirect consequences of herbicide use exist at two levels. First, there are potentially adverse consequences for wildlife as a result of the intended outcome of herbicide use, namely the elimination or at least significant reduction in wild plant density and diversity within the crop. Secondly, herbicides have adverse, indirect consequences through facilitating particular systems of crop production, such as simplification of crop rotations or drilling to a stand, which also have consequences for reduced biodiversity in intensive farming systems. This latter class of indirect effect is not dealt with in this review, but does have implications for the development of sustainable farming systems.

Bunyan & Stanley (1983) recognised that indirect effects from pesticides in the UK had received much less attention and were more difficult to identify, assess and rectify, but were potentially as significant as direct effects. They concluded that there were well established cases of indirect effects of pesticides on flora and fauna citing the grey partridge (*Perdix perdix*) as an example. Southwood & Cross (1969) suggested that a prime reason for the decline in partridge breeding success was poor chick survival following the widespread introduction of herbicides into cereals in the 1950s. This was attributed to a major decline in abundance and biomass of those invertebrates dependent on weed species in the crop and on which the chicks feed during the first 6 weeks of their life. Subsequent modelling of grey partridge populations has supported the significant role played by this reduction in prey availability in lowered chick survival and decline in partridge populations (Potts & Aebischer 1995), although other factors (predation rate and nesting cover availability) are also important.

Serious declines in other farmland bird species, especially those classed as seed eaters, have taken place more recently (although for some, such as the corn bunting (*Miliaria calandra*), there is evidence for a longer-term trend); in a number of species, especially linnet (*Carduelis cannabina*), tree sparrow (*Passer montanus*), corn bunting and skylark (*Alauda arvensis*) herbicides have been implicated (Marchant *et al.*, 1990, O'Connor, 1992). Paradoxically, these national declines were taking place during the 1970's and 1980's when overall weed abundance in summer in the main partridge study area of The Game Conservancy Trust remained constant, as did partridge chick survival rate (Potts & Aebischer, 1995, Aebischer, 1991). However, whereas herbicide use in cereals was already widespread in the 1950s, initial impact was on dicotyledonous weeds. This was followed in the 1960s by an increasing use of selective herbicides in row crops thereby broadening the effects on dicotyledonous plants; during the 1970s there was also increasing use of herbicides to control grass weeds. Such a pattern of changing herbicide use would be consistent with a hypothesis that whilst the grey partridge decline is attributable in part to a reduction in the weed food supply for their invertebrate prey in spring, it may be the decline in winter weed seed availability that has played a major role in the more recent declines of other bird species. Many of the latter species rely on smaller weed seeds including grass seeds, chickweed and fat-hen. Chickweed and fat-hen were still abundant at the end of the 1960s (Fryer & Chancellor, 1970) but have declined since. Direct evidence for effects on such bird species is still lacking, however Green (1978) showed that skylarks switched to grazing young seedlings in areas where winter seed availability was reduced - a less favourable strategy energetically. In this species indirect effects operating via a reduction in the availability of herbivorous invertebrate prey in spring may also be important, as the feeding ecology of young skylark chicks appears analogous to that of grey partridges (Poulsen & Sotherton, 1993). In some cases for example the reed bunting (*Emberiza schoeniclus*) in the UK and duck species in the US prairies, it has been suggested that the effect on cover for nesting may also have been important (O'Connor, 1992, Freemark & Boutin, 1995).

The most compelling evidence for the importance of indirect effects of herbicides comes from comparative studies between areas with higher or lower inputs of herbicides. Thus in Conservation Headlands where little or no broad-leaved weed herbicides were used in spring or summer in a 6m strip of crop adjacent to the field boundary, mean partridge brood size was significantly higher as was chick survival rate, and pheasant brood size also increased in such selectively sprayed strips (Sotherton *et al.*, 1989). Experimental evidence for the importance of indirect effects of herbicides on other bird species is not available. Green *et al.* (1994) showed that the incidence of many common bird species was in fact lower in hedgerows adjacent to autumn cereals which had received reduced herbicide use; however a significant difference was only apparent in non seedeating species or for species which are not undergoing a decline. So these findings are not inconsistent with herbicides affecting other seedeating species which were insufficiently abundant to show significant differences in this study.

Effects of herbicides on soil fauna may often be due to their indirect effects, through habitat modification (such as effects on humidity) or availability of decomposing plant matter (Fox, 1964, Edwards & Stafford, 1978). Several studies have shown increased occurrence of butterflies in Conservation Headlands (Dover *et al.*, 1990, Sotherton *et al.*, 1989) and there is some evidence to suggest that populations themselves may be enhanced. It is likely that the removal of broad-leaved hosts for caterpillars during grassland improvement has had a local effect on butterfly populations in grassland (Bunyan & Stanley, 1983). Other invertebrates which have increased in abundance in Conservation Headlands include Heteroptera and Carabidae (Hassall *et al.*, 1992), in the latter case it appeared that increased availability of invertebrate prey was an important factor (Chiverton & Sotherton, 1991). There is less evidence for an indirect effect of herbicides on wild mammals. In the US use of 2,4-D altered the food availability for two out of four small mammal species studied (Freemark & Boutin, 1995). In the UK, Tew *et al.* (1992) discovered that wood mice (*Apodemus sylvaticus*) foraged preferentially in selectively sprayed headlands, apparently in response to higher food (weed seed) abundance.

EFFECTS OUTSIDE CROPPED AREAS

Herbicides may contaminate nearby semi-natural habitats by a variety of mechanisms. But herbicide levels off-target should be lower than on the cropped land and consequently carry a lower risk of effects. Because of the exponential manner in which residues from droplet drift decline away from the cropped area, adjacent linear habitats will be most at risk. Still water ditches are especially vulnerable because of their small size and lack of dilution via flow and also because they can be contaminated by other routes, such as by surface run-off and drainage flow. In a major collaborative study at the Agricultural Development and Advisory Service farm at Rosemaund, Hereford (Matthiessen *et al.*, 1994, Williams *et al.*, 1995, Mitchell, 1995) most of the pesticides studied peaked transiently in a stream immediately following rainfall, because the rain carried residues via macropores to field drains and thence to the stream. For technical reasons plant bioassays were not deployed in the stream, but herbicide concentrations were sometimes attained at which damage to macrophytes or algae would be expected (Mitchell, 1995).

Herbicide residues are frequently found in surface waters and give rise to concerns for drinking water supplies (eg Ashby-Crane *et al.*, 1994). Despite the fact that aquatic contamination might affect macrophytes and algae and have knock-on effects on fauna, there has been relatively little monitoring of freshwater plants. Monitoring tends to be concentrated on invertebrate communities which are less likely to be affected directly by herbicides. In a plant monitoring study referred to by Ashby-Crane *et al.* (1994), in the Crossens catchment in north west England, spatial changes in macrophyte diversity have been recorded and pesticides are believed to be a major contributory factor.

In view of the known toxicity of specific herbicides to aquatic plants and perhaps directly to aquatic fauna, buffer zones have been introduced in the UK to protect aquatic life. Examples in Anon (1995) include buffers for metsulfuron-methyl to protect aquatic plants and for linuron to protect aquatic life. These buffers were introduced primarily to safeguard against overspraying but are currently being reviewed to bring the assessment process in line with the requirements of Directive 91/414/EEC.

A number of products have other safety precautions to minimise off-target contamination (Whitehead, 1995). For products containing atrazine and simazine, users are advised to plant grass strips 6 m wide between treated areas and surface waters to reduce surface run-off. Some herbicides carry warnings about avoiding drift onto nearby crops eg for metsulfuron-methyl.

Herbicide drift affecting native terrestrial flora has been studied in a series of experiments summarised in Cooke (1993). Lichens tended to be comparatively resistant but direct spraying should be avoided. Drift effects on higher plants were rare 8 m downwind, including in mesocosm community trials. But effects on seedlings of higher plants could occur up to 20 m. Thus a population of rare species very close to arable land or more common species occurring in crop-side habitats would be at risk.

Changes in hedgerow flora are likely to have reflected both the unintentional impact of herbicide and fertilizer drift into field boundaries, and the deliberate management of field boundary flora. The latter may include the intentional use of translocated herbicides to control weeds perceived as likely to spread into the crop, and this has had a severe effect. Several experimental studies have shown that fertilizer use can have an impact on field boundary flora and that plants there may be adversely affected by herbicides applied at rates approximating to spray drift levels (eg Marrs *et al.*, 1993). There is however little direct evidence for such effects of herbicides in practice; no field boundary botanical changes, which could be associated with differences in herbicide use, were found in studies on two farms (Marshall, 1987). The botanical composition of field boundaries in intensively cropped areas may have become adapted to periodic spray drift over many years (Marshall, 1992), in which case relaxation in herbicide pressure may not result in any major change, or may take many years to become apparent. The significance of herbicide drift for field boundary flora therefore remains to be determined.

Information on "environmental incidents" with named herbicides has been taken from the reports compiled by the Field Operations Division of the Health and Safety Executive over the four year period 1989/90-1992/3. Out of a total of 101 incidents, most concern centred on gardens being affected or at risk (62 reports). There were 13 reports relating to semi-natural vegetation: reserves 3, woods/trees/hedges 7, footpaths/verges 3. Although reports of serious direct toxic effects on off-target vegetation are relatively few, we have no information on the likelihood of an individual incident being reported. Also subtle shifts in community structure would be difficult to detect and it is more likely that effects have been directed via this route because of repeated exposure - as for native plants in the crop.

Applying herbicides from the air can result in effects hundreds of metres downwind (Payne, 1992, Marrs *et al.*, 1993). However, such effects are not currently an issue in intensive farming as aerial spraying of herbicides is now more or less restricted to asulam applications in low intensity farming systems (Thomas & Deverson, 1995). This, however, has not always been the case as a comparison of the statistics for 1984 and 1994 reveals (Table 2). In the past, a greater range of herbicides was used, mainly on cereals. Although the scale of aerial application of herbicides was not great, application of products containing active ingredients such as isoproturon (recorded use 1321 ha in 1984) had the potential to cause incidents of conservation significance. Although not now being used in this way, isoproturon is still approved for aerial application (Whitehead, 1995).

Table 2 Aerial application of herbicides in 1984 and 1994 (Pesticide Usage Survey Group reports number 60 and 126 (provisional)).

	1984	1994
Number of active ingredients	≥18	2
Number of spray occurrences	101	168
Total area treated (ha)	6918	8646
Cereals as % of total area	83	1
Bracken as % of total area	15	99

SOME RECENT TRENDS IN HERBICIDE USE

On crops such as cereals, usage surveys have revealed little change over recent years in the area sprayed, but a decrease in the tonnage of active ingredients applied. For instance, Davis *et al.* (1993) reported a 1% increase in area of cereals treated with herbicides from 1990 to 1992, but a 21% reduction in the amount of active ingredients applied. This effect generally reflected "a change to products applied at lower rates of active ingredients per hectare".

There is, however, another change that could produce this effect, namely a reduction in dose rates for existing active ingredients. This distinction is potentially important as substitution of more active, lower dose compounds may not reduce the risk of adverse effects on wildlife, whereas a general reduction in dose rate may bring benefits. The Pesticides Safety Directorate (PSD) Annual Report for 1993/94 (Anon, 1994) drew attention to the Government's Minimisation Policy, outlined in the 1990 White Paper (Anon, 1990), and mentioned that survey information from arable producers in 1992 indicated that products were regularly applied at well below the recommended rate.

In order to try to differentiate between these two factors, both of which may reduce tonnage applied, we have examined data from the Pesticide Usage Survey Group (PUSG) for herbicides on wheat (Table 3), based on herbicides sprayed on >100,000 ha in 1992. Data were abstracted for England and Wales in 1988 and 1990 and for Britain in 1992 and 1994 for these herbicides when used as single active ingredients in products. For Scotland in 1988 and 1990, such data were not available in the reports and data on total use of active ingredients in all products were abstracted instead to help provide composite figures for Britain. Three herbicides that are applied at low rates (all <0.2 kg/ha) have shown overall increases in use during this period: fenoxaprop-ethyl, fluroxypyr and metsulfuron-methyl. Mecoprop has been largely replaced by mecoprop P. The remaining four herbicides in the Table have shown no consistent trends.

In addition, however, there is evidence of dose rates for these herbicides decreasing. This trend clearly began before the publication of the Minimisation Policy in 1990 and there is evidence that the trend was not so marked between 1992 and 1994.

Table 3 Spray hectares and computed mean dose rates for some commonly used herbicides on wheat in Britain (PUSG reports number 77, 78, 85, 87, 108 and 127 (provisional)).

Herbicide	1988		1990		1992		1994	
	Area (1000 ha)	Rate (kg/ha)	Area (1000 ha)	Rate (kg/ha)	Area (1000 ha)	Rate (kg/ha)	Area (1000 ha)	Rate (kg/ha)
Chlorotoluron	175	2.68	149	2.83	128	2.71	281	2.38
Fenoxaprop-ethyl	0	-	185	0.14	430	0.11	241	0.08
Fluroxypyr	238	0.17	364	0.16	668	0.14	593	0.13
Glyphosate	167	0.80	72.7	0.74	152	0.78	126	0.76
Isoproturon	816	2.00	831	1.75	669	1.65	872	1.52
Mecoprop	820	2.16	523	1.88	148	1.29	226	1.35
Mecoprop P	35.8	1.25	87.5	1.03	415	0.87	405	0.87
Metsulfuron-methyl	318	0.0055	308	0.0054	370	0.0047	561	0.0048
Pendimethalin	110	1.34	135	1.20	166	0.99	58.9	0.83

Significance levels for differences in mean dose rate by paired t tests examining proportional changes: 1988 vs 1990, $P < 0.05$; 1990 vs 1992, $P < 0.01$; 1992 vs 1994, $0.1 > P > 0.05$.

To look at trends in application rates on other arable crops, we have abstracted information from the PUSG reports for the same period for herbicides used on >50,000 ha in 1992 on winter barley, oil seed rape, linseed and potatoes. We avoided data for spring barley as it is widely grown in Scotland, for peas and beans because the data were not separated for the two crops in the 1988 report and for sugar beet because it was not covered in the 1988 report. We used readily available data for England and Wales in 1988 and 1990 and British data for 1992 and 1994. Application rates in the 17 crop/herbicide combinations that resulted showed significant overall declines between 1988 and 1990 ($P<0.05$) and between 1990 and 1992 ($P<0.001$) but not between 1992 and 1994 ($0.1>P>0.05$). So results were consistent with those for wheat (Table 3).

CONCLUSIONS

Evidence is assembled here to suggest that herbicides have caused a range of effects on fauna and flora living on or close to farmland. In the main, common species have been affected, with first a reduction in abundance and secondly a contraction in range. A question that can legitimately be asked is "Does it matter?". Cooke (1990) has argued that a single product that causes a direct, long term or permanent effect on a population of a non-target species is likely to be unacceptable. Here, a class of pesticides may have had measurable effects on national populations of wild species, birds for example. Effects on this scale should be taken very seriously even though they are occurring indirectly. Where the affected native species also happen to be target species, ie the weeds, the nature of the debate is rather different. But if those species decline to below the level at which they are of economic significance, they should then be regarded as non-target species. If they become rare or even endangered, eg the pheasant's-eye, positive efforts should be directed at their conservation.

Our ability to produce unequivocal evidence for a wide range of environmental effects has been confounded for three principal reasons. First, some species that have probably been affected, eg aquatic macrophytes, have been little studied. Secondly, other species, eg rare arable weeds, have been exposed to significant changes in a number of other environmental variables in addition to increasing herbicide use. Thirdly, some species, such as birds, may have been affected indirectly rather than directly, and such effects are especially difficult to unravel. There is an urgent need for in depth reviews to pull together information on important topics and perhaps identify multifactorial studies that can tease out herbicide effects. There is a need for targeted bioassay studies, for instance, along the lines of the aquatic plant technique developed by Hatakeyama *et al.* (1994). But it is important that such studies do not delay remedial action. There is much to be said for a pragmatic approach of varying herbicide regimes and monitoring the outcome with a view to adopting strategies that minimise effects.

Effects on wildlife appear to be largely governed by the intensive and extensive nature of spraying and by the properties of herbicides. Simply switching to low dose active ingredients with similar properties (eg spectrum of activity and persistence) will not help to lessen environmental effects although it might be seen as part of a strategy to meet stringent drinking water requirements. There does, however, seem to be considerable potential for improvement by modifying frequency of use, method of application etc and perhaps by developing and encouraging use of more specific selective herbicides with more benign properties (eg lower persistence, no significant toxicity to animals). We therefore welcome the evidence presented here for reductions over time in application rates. However, the start of this trend pre-dates the introduction of the Minimisation Policy and it is not clear to what extent trends are being either actively driven or monitored by Government. Indeed it seems that the trend is beginning to slow down. Reductions in herbicide use will bring greater benefits for wildlife if they are monitored and understood and then guided towards focussed, if unquantitative, goals. For instance it might be possible to focus reductions spatially, temporally or chemically on those uses known to be especially damaging for wildlife. Trials presently under way can be used to indicate the level of environmental improvement that may be expected from changes that are agronomically feasible. Interim results from the MAFF TALISMAN programme, which seeks to compare the effects of differing inputs of pesticide and fertilizer in large scale trials (Young, 1995), have shown that increases in both weed density and diversity may under some circumstances be achieved by reducing herbicide use in conventional agricultural systems without compromising yields. Whether any increases in plant biodiversity achieved in this way might be significant in ecological terms still remains to be determined. However, the pressures for crop hygiene and perceptions of crop cleanliness make it unlikely that such changes will rapidly result in the overall level of recovery (especially from indirect effects) that conservationists would like to see. To achieve this, opportunities must be taken to maximise fully the potential of land not being intensively farmed on either a temporary or long-term basis, eg setaside.

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TECHNOLOGY DEVELOPMENTS IN WEED CONTROL AND TARGETING FOR REDUCING ENVIRONMENTAL IMPACT

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ABSTRACT

This paper proposes that the environmental impact of current weed control practices can be reduced without adversely affecting the economic viability of farming by promoting the adoption of suitable new technologies rather than by withdrawal of herbicides. Trends in chemical, biological and physical weed control, genetic resistance to herbicides in crops, improved application techniques and uses of information technology are discussed. Combinations of approaches may be synergistic in effect. Issues related to the adoption of innovations are briefly considered.

INTRODUCTION

Modern agriculture is highly dependent on the use of herbicides. They are seen as critical tools in maintaining economic sustainability for most farmers, and consequently contributing to social sustainability. Nevertheless, the environmental sustainability of the current approach to herbicide use is a matter of contention. The organic/biological farming movement attempts to farm without modern pesticides but there may be environmental costs associated with their approach which are perhaps not yet fully understood. In addition, in a global context it is likely that most farmers could not readily be convinced to dispense with herbicides as at least part of their armoury, and that the world demand for food could not be supplied by organic systems. So can the use of herbicides (as well as other such inputs) be modified or developed to minimise or reduce their environmental impact? There are two approaches: (a) restrictive (e.g. Denmark has recently banned the use of mecoprop, and MCPA from arable fields because of detection in water); (b) promotion of new technology (that is using technology to overcome environmental problems).

This review will focus on technological developments which could reduce the impact of weed control practices on the environment, without adversely affecting farm outputs or the social and economic sustainability of farming. It will concentrate on 'hardware' such as chemical, biotechnology and engineering innovation in methods of application, and also 'software' such as information technology, decision support systems and remote sensing. It will ask whether apparently useful weed control technologies have been partially developed and then not come to fruition, and whether there are technologies in the pipeline which could prove beneficial to the environment within 5-10 years, given appropriate adoption incentives. The review has been developed using literature searches and interviews with weed scientists.

DEVELOPMENTS IN WEED CONTROL

Trends in herbicide activity and safety

Table 1 lists the active ingredients (AIs) reported as new compounds in the proceedings of the conferences on weeds and weed control held at Brighton since 1953, with additional information on important AIs developed since 1942. The herbicides of the 1940's and 1950's were used at mean dose rates of 1000-3000 g AI/ha (see column c in Table 1). In the mid to late 1970's newer materials were regularly active below 1000 g AI/ha with fluridone reported active at 100 g AI/Ha. The major breakthrough came with the development of the sulfonyl-urea group. Chlorsulfuron was reported in 1980 as active around 15 g AI/ha, followed by metsulfuron-methyl at 6 g AI/ha in 1983. At the 1993 Brighton Crop Protection Conference the new compounds were active at 5-10 g AI/ha to 30-90 AI/ha, with only one other requiring more than 100 g AI/ha. This dramtic reduction in the application rate per hectare of the newer herbicides has been widely regarded as providing an environmental benefit in terms of the total environmental load of chemicals. However, if this trend merely means that the chemicals concerned are becoming more potent, then the environmental benefit may be an illusion. For comparison, Table 1 also lists in column b the rat oral LD50 as an indication of the potential impact on non-target organisms, although this is a rather crude measure of the possible overall environmental impact of a herbicide. If one accepts the above line of argument, an environmentally safer situation would be one where the application rate/ha of new AIs is declining over time (column c, Table 1) and at the same time there is a stable or increasing trend in the figures for LD50 (column b, Table 1). With this in mind, Table 1, column d, gives the 'toxicity ratio' (application rate of AI/LD50). A declining trend over time in this ratio is seen as a more valid indicator of improvements in environmental safety of new products than reliance on the application rate alone. For example, metsulfuron-methyl, introduced in 1983, is active at 6g AI/ha, with a rat oral LD50 of >5545 mg/kg (toxicity ratio1), whereas that of MCPA, introduced in 1945, which it has partially replaced, is used at 2000 g AI/ha with a rat LD50 of 700 mg/kg (toxicity ratio of 2857) (Table 1). The mean toxicity ratios from Table 1 are: 1942-69, 1670; 1970-79, 689; 1980-89, 173; and in the 1990s, 58, indicating a generally favourable safety and environmental trend according to the above analysis. This analysis ignores the fact that highly active herbicidal materials may also be more active on non-target plant species and so accidental spray drift may be more hazardous environmentally than with some of the older, less active products. A small error in dose rate could also have a greater environmental impact than from a less active compound. However this has to be balanced against the apparently lower hazards arising from normal commercial usage.

Generic Products

Increased costs of maintaining off-patent products in the market place has meant the loss of a number of herbicides for commercial, rather than safety, reasons. Products deemed to pose a reduced risk to human or environmental health could disappear due to lack of commercial interest rather than due to a lack of farmer usage. The Environmental Protection Agency of the USA is considering extending the patent life of such pesticides to encourage their commercial survival through the development of a pilot scheme in which registrants are invited to submit a rationale for their product (Anon, 1993).

Future Chemistry

New high activity compounds tend to have a narrow range of targets, which can be an environmental benefit, but causes some concern to weed scientists. For example many are fatty acid inhibitors. The dominance of such groups will increase the risk of the development of weed resistance which may be of environmental concern. The dominance of single areas of chemical activity in the cropping system may also have an impact in terms of cumulative residual biological activity. Although individual treatments may leave very low residual activity levels, continued use of similar AIs may lead to shifts in species balance. For instance, UK farmers could, within a few years, be using products mainly from two chemical families to control weeds in rotations with cereals/rape/
potato/sugar beet and even grass: phenoxy-type grass herbicides ('-fops and-dims') and sulfonyl-ureas. Farmers may have to be encouraged to diversify their herbicide usage, above that which makes strict economic sense, for longer term weed resistance control, and possibly for other environmental benefits.

The development of natural chemical products as herbicides, including allelochemicals, has little commercial interest because of the lack of patent protection for such materials. There is also no clear evidence that such chemicals would be safer to the environment if used on a large-scale although some members of the flora and fauna may have adapted to break-down and utilise such products. Agrochemical companies have an interest in modifying such molecules to improve activity and to enable patenting but this may negate potential improvements in environmental impact.

Reduced environmental loading has been achieved by developments in molecular chirality which has allowed a reduction in herbicide dose. For example, the mecoprop-p isomer can be used at approximately half the dose of the isomeric mixture, mecoprop, with an aproximately 50% reduction in the toxicity ratio (Table 1).

Chemical safeners can allow the use of newer environmentally benign active ingredients on crops that are otherwise sensitive to them. Their action is usually to enable the crop plant to metabolise the toxic chemical without reducing its toxicity to target weeds (Kreuz, 1993). In the 1970's Stauffer produced an antidote (dichlormid) to the maize herbicide EPTC which allowed higher doses to be used to control certain weeds (Chang *et al.*, 1972, vide Worthing and Hance, 1991). While this may have been 'safer' for the commercial crop, it does not represent an environmental benefit. There are a number of more modern materials such as fenchlorazole-ethyl which is used to safen fenoxaprop-ethyl, and later the fenoxaprop-p isomer, for use as a grass herbicide in wheat (Foster *et al.*, 1993). The latter product allowed the use of 70 g/ha AI (toxicity ratio 23) compared with earlier products requiring 600-1000 g AI/ha (e.g. difenzoquat, toxicity ratio 1596; flamprop-M, toxicity ratio 150), for similar activity on *Avena fatua*.

Pesticide formulation to facilitate use by the farmer has received increasing attention, in part driven by requirements to improve product efficacy and safety to the environment, user and consumer (Towson, *et al.*, 1995); for example replacing solvent-based compounds with solids or water-based formulations. Spray adjuvants (such as wetters, spreaders, penetrants and stickers) can be added to modify activity further (Stock, 1991). In a review of their use in the USA, Foy (1993) suggested that such adjuvants enhanced or had no effect on activity, but there was little experimental evidence; nevertheless only 3% of farmers did not use them. Davies and Hinchcliff (1989) suggested that combinations of herbicides and adjuvant could be antagonistic in some situations. Nevertheless, in our advisory experience, many British farmers use them in an indiscriminate manner and the technology is popular.

Where proper experimentation has been undertaken clear associations between specific adjuvants and certain herbicides have been demonstrated. Certain chemical groups such as phenoxy grass herbicides are particularly assisted by penetrants or wetters and sulfonyl-urea cereal herbicide activity is enhanced by certain silicone-based and alkoxylated fatty amine polymer adjuvants (e.g. Davies and Wilson, 1995). This complements results elsewhere. However, many practical applications of adjuvants have developed in a serendipitous manner and Kirkwood (1993) has emphasised the need for guidelines for optimising combinations of herbicides and adjuvants. Holloway *et al.*, (1989) have looked at non-ionic surfactants to produce predictive models of activity.

If the environmental loading of pesticides is reduced by adjuvants, this can be considered a benefit. However, some adjuvants may be more toxic to flora and fauna than the pesticides, and safety testing should be equally rigorous. Nevertheless, this area may present significant advances in reducing active chemical loading and improving targetting.

<u>New herbicide developments not being taken forward to market.</u>

An active ingredient with a major market potential would not fail to be supported by the inventing company if it could be protected by a patent and had no safety or toxicological problems. Non-patentable chemistry of clear benefit may however, not be developed. Furthermore, if herbicide products fail to work in the major markets of wheat, maize, rice, soyabean and cotton, they are unlikely to be developed for other crops because of the high cost of R & D. From a survey of literature and colleagues, the following compounds could have been developed for our conditions but have not been, probably for commercial reasons.

(i) Tridiphane, a graminicide developed by Dow, prevented atropine breakdown in certain weeds. Trials have shown that it may improve the activity of isoproturon and cyanazine, potentially allowing dose reduction (J Caseley, IACR, personal communication). In the light of concerns regarding isoproturon appearing in surface waters, this may have been a useful development, and may have assisted in the long-term retention of isoproturon.

(ii) SMY1500 was developed for control of grasses in cereals, including *Bromus sterilis* (Hack et al, 1985), which is treated with high doses of isoproturon. As the weed often occurs on the edge of fields, possibly near to water sources, this increases the potential for contamination of water with isoproturon. It is believed that the market was considered too small by Bayer.

It is not clear how such technologies can be brought to market without considerable public investment if they are not of interest for the major cropping situations.

Biological control developments

A few fungal-based products have been developed for the control of weeds such as DeVine® and Collego®, respectively incorporating *Phytophthora citophthora* for control of *Morrenia odorata* (strangler-vine) in citrus orchards and *Colletotrichum gloeosporoides* f.s.p. *aeschynomene* for *Aeschynomene virginica* (northern joint-vetch) control in rice and soyabean in the USA. Another six products had been used, or were near marketing by 1992 (Greaves, 1992). However, DeVine® and Collego® have now been withdrawn, probably because of small market size, and other products (eg Casst®, Doctor Biosedge®) have failed for cost of registration or market reasons. Possibly the only successful product is Luboa, a Chinese government product based on *Colletotrichum gloeosporoides,* which is sold very cheaply for control of *Cuscuta spp* in rice.

Such products are likely to be very target-specific but farmers using Collego® and DeVine® were willing to tank-mix them with other herbicides. The lack of success maybe due to the lack of a large marketing and development organisation in small companies. The agrochemical companies find it difficult to target this area because natural organisms cannot be patented, making such developments reliant on public funding, at least in part.
The genetic manipulation of organisms for increased or specific pathogenicity may be the most promising approach for mycoherbicide performance (Greaves, *et al.* 1989) as well as for improving the performance of other biological herbicides, for example by modifying the feeding behaviour of arthropods. However, this awaits a resolution of patenting issues as well as scientific and philosophical debates regarding genetic manipulation (Davies, 1995).

Physical control developments

Mechanical cultivation techniques, thermal-systems and mulches can be very effective, but often need skilled operators. Mulches are used in crops of higher value, but mechanical methods are used in a wider variety of crops. New technology is assisting in the problem of in-row weeding. If the range of herbicides available for minor crops depletes seriously then the use of physical means of control will become important; possibly integrated with chemical treatments. Van der Weide *et al.* (1995) suggest that such techniques could be generally adopted in the Netherlands to allow a reduction in herbicide loading with no economic loss . Herbicides could be replaced by physical control or, as described by Blair and Green (1993), by use of very low doses of herbicides to weaken weed growth to improve the impact of the mechanical operation. The environmental benefits lie in reduced herbicide loading and leakage, but this may be offset by extra machinery costs and environmental impacts.

Herbicide resistant transgenic crops

The first transgenic crops resistant to glyphosate and glufosinate-ammonium are currently being registered in a number of countries. Resistance to environmentally benign herbicides could reduce the use of less benign materials. This is not, however, without its concerns, notably in terms of the spread of introduced genes into the natural environment and the problem of volunteer crops resistant to benign herbicides which may encourage increased use of less benign alternatives where these crops become weeds in other parts of the rotation (Lawson, 1993). For example glyphosate resistant oilseed rape may have to be controlled with MCPA or a similar product with a toxicity ratio of over 2000, compared with glyphosate with 214 (Table 1).

Application of herbicide

The use of mixtures and sequences of low doses of herbicides, particularly the more recently developed materials (Table 1), can reduce overall the amounts of herbicide used on farms. Precision in timing of application, weed/dose targeting and an appreciation of the appropriate conditions in terms of crop/weed relationships and weather are particularly important. Funding in this area is now limited in the UK, but for example in France, funding by government and farmer levy aids a major programme on evaluating the dose required for each herbicide product on individual weeds (Orlando et al, 1993).

Better use of conventional sprayer technology may prove of some environmental benefit. The use of low-drift nozzles and precision application, including 'wiper' applicators, air-assisted sprayers, shrouds and deflectors, can all reduce the impact of the drift from spray treatments. Spillages of concentrates can be reduced by use of closed transfer systems, refillable containers, injection systems, closed low volume tank wash systems and specialised waste collection systems. Better maintenance of sprayer systems could be encouraged by the development of a sprayer 'MOT' testing system. Newer sprayers have a range of features to assist in reducing drift and spillages but training of operators should emphasise the need to minimise environmental impacts.

The imposition of 6 m 'buffer-strips' alongside surface water bodies suggested by the UK Pesticide Safety Directorate for many products should improve environmental protection from drift. However, unless the strip is on relatively flat land, it may be insufficient to prevent surface movement of pesticides. Design of buffer strips to prevent surface movement of pesticides to areas of environmental sensitivity requires further research but there is a potential for environmental gains. However, sub-surface movement of pesticides is not stopped by simply leaving an untreated strip of land, and presents considerable design problems (Davies and Christal, 1995). The use of 'buffer-strips' could be associated with field margin set-aside regimes, and agricultural environmental schemes such as the current Scottish Office Habitats Scheme where finance may be available for the protection of waterside habitats on certain rivers.

Precision treatment

There is considerable research being undertaken on the precision treatment of weeds by mapping weed patches, and storing tthe information on computer systems which control the sprayer, to treat only where the map indicates the presence of the weeds. Such approaches, using satellite-based geographical positioning systems or land-based beacons could lead to reduced and more precise herbicide use (Miller and Paice, 1995). The modification of dose and herbicide content dependent on weed type and density may also be possible. Research is also being carried out on identifying weed species by image analysis (Gerhards *et al.* 1995), and by light wave-band reflectance (F. Hahn, SAC; personal communication). This requires increasing computer and sofware power to produce the rapid response times needed to control the applicator. However, these approaches could lead in the longer term to more precise targeting of weeds.

TABLE 1. New herbicides reported at the Brighton conferences and other important active ingredients listed by (a) year, (b) rat oral LD50 (mg/kg), (c) common dose rate (g AI/ha) and (d) toxicity ratio (c/b).

Herbicide	(a)	(b)	(c)	(d)
2, 4-D	42	375	1500	4000
MCPA	45	700	2000	2857
TCA	47	4100	15000	3658
mecoprop	56	930	2000	2150
atrazine	57	2475	2000	808
barban	58	1400	2000	1429
trifluralin	60	>10000	1100	110
dichlorprop	61	800	2700	3375
linuron	62	4000	900	225
ioxynil	63	110	500	4545
picloram	64	8200	2000	244
propachlor	64	1800	5000	2778
benazolin	64	>4800	770	160
siduron	64	>7500	7000	933
chlorbromuron	66	>5000	1000	200
nitralin	66	2000	1000	500
phenmedipham	67	8000	1000	125
cyanazine	68	288	1000	3472
ethofumesate	69	>6400	1000	156
bentazone	70	1100	1700	1545
chlorotoluron	70	>10000	2000	200
metoxuron	70	3200	3200	1000
propyzamide	70	6985	1500	215
oxadiazon	70	>8000	1500	188
methazole	70	2500	1500	600
glyphosate	71	5600	1200	214
piperophos	72	324	900	2778
metolachlor	74	2780	1500	540
ethalfuralin	74	>10000	1100	110
dimefuron	74	2000	1000	500
pendimethalin	74	1250	1300	1040
difenzoquat	74	470	750	1596
bifenox	74	6400	1250	195
metamitron	75	2590	4000	1544
isoproturon	75	2700	1500	556
fluridone	76	10000	100	1
pyridate	76	2000	1250	625
flamprop-m	76	>4000	600	150
tebutam	76	6210	3000	483
alloxydim-sodium	78	2300	900	391
chlorsulfuron	80	5920	15	3
fluazifop	80	3330	750	225
sethoxydim	80	3200	250	78
fenoxaprop	82	2400	250	104
imazamethabenz	82	>5000	510	102
isoxaben	82	>10000	125	13
metsulfuron	83	>5545	6	1
diflufenican	85	>2000	100	50
tribenuron	85	>5000	30	6
thifensulfuron	85	>5000	30	6
triasulfuron	85	>5000	8	2
quinmerac	85	>5000	500	100
cycloxydim	85	3490	150	43
imazethapyr	85	>5000	100	20
tralkoxydim	87	1100	200	182
prosulfocarb	87	1900	3000	1579
pirimisulfuron	87	>5050	25	5
clethodim	87	1490	140	94
propaquizafop	87	>5000	120	24
DPX-A7881	87	>1100	80	7
flurtamone	87	500	500	1000
mecoprop-P	87	1050	1200	1143
DPX-E9636	89	>5000	10	2
fenoxaprop-p	89	3015	70	23
nicosulfuron	89	>30000	40	1
fluoroglycofen-ethyl	89	1500	30	20
isoxapyrifop	89	950	75	79
quizalafop-p	89	1200	90	75
clodinafop-propargyl	89	1829	60	33
DPX 66037	91	>5000	25	5
NC319	91	8865	50	6
NC330	91	>5000	125	25
KIH 2031	91	3000	70	23
flupoxam	91	>5000	150	30
S-53482	91	>5000	75	15
F6285	91	2855	430	151
HC252	91	900	20	22
SAN5824	91	1570	1000	637

Herbicide	(a)	(b)	(c)	(d)	Herbicide	(a)	(b)	(c)	(d)
F8426	93	5143	30	6	CGA 152'005	93	986	20	20
KIH 9201	93	>5000	8	2	ET 751	93	>5000	9	2
metobenzuron	93	40000	190	19	KIH 2023	93	3400	30	9
thidiazimin	93	>1000	30	8	KIH 6127	93	>5000	60	12

Data derived from Proceedings 1-12th Brighton Weed Control Conference (1953 - 1974), proceedings of 1978/80/82/85/87 British Crop Protection Conference - Weeds, Brighton Crop Protection Conference - Weeds 1989/91/93, and the Pesticide Manual 8th Edition (Worthing and Walker, 1987) and 9th Edition (Worthing and Hance, 1991).

INFORMATION TECHNOLOGY

Information technology (IT) underpins many of the potential technological improvements outlined above. The potential of modern IT systems to handle large amounts of data quickly allow greater control of herbicide application and selection. Decision support systems (DSS) are designed to aid the adviser or farmer to come to management decisions on a consistently more accurate basis. The data entered into the system has to have a firm knowledge-base and it must be easy to use. The most advanced system available, PC-Plant Protection from Denmark, which includes both experimental results and 'expert knowledge' as the basis for a herbicide and dose selection program (Baandrup, 1989), is considered very robust, perhaps in part due to a degree of conservatism. As more information on herbicide, weed and crop behaviour is added, then dose modification could be more radical (Rydahl, 1995), with other factors such as environmental impact being added to the herbicide selection process. Combellack and Pritchard (1990) suggest the grading of pesticides on an environmental impact basis, which has apparent attractions but is fraught with difficulties in deciding the boundaries of characteristics. However, the approach may appeal to organisations managing areas of environmental sensitivity and could be included in a DSS.

ADOPTION

Rogers (1963) noted five characteristics that affected the rate of adoption of 2,4-D in the USA: relative advantage (economic or convenience), compatibility (with current practices and values), complexity (farmers considered 2,4-D a complex innovation and this slowed adoption rate), divisibility (can it be tried on a small scale first), communicability (ease of transfer of an idea). He suggested that the first adopters are generally younger, wealthier, larger farmers. Farming communities 30 years later probably still have the same characteristics. Busch (1993) recognised that the transfer of technology is undertaken by translation into current systems and that where new technologies merely replace older ones the increased cost of adoption is negligible. Greater degrees of change are more difficult but is possible. Busch suggested that in the USA higher yield (maize) varieties were 'diffused by convincing some farmers to re-organise their fields .... so they more closely resemble the researchers' experimental field'. Those who benefited were those who had most capital to do this, whereas those who could not change lost their farms. He points out that as the complexity of technology increases more off-farm servicing costs may be incurred. The importance of a capital base or financial assistance in encouraging adoption of innovation is clear. However, some environmentally beneficial adoptions may require corporate or civic adoption rather than adoption by individuals (Busch, 1993) or a more positive civic approach and perhaps legislative change. The introduction of novel technologies and ideas has often come through extension services, publicly or privately funded, and this is an area where better training could encourage greater awareness of environmental issues. However, without evident financial benefits innovations are unlikely to be accepted widely. The use of legal restrictions, artificial price supports or cost penalties, may still be required to encourage the adoption of many potentially beneficial innovations, along with an element of public funding.

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CROP TECHNOLOGY: A FLEXIBLE FRIEND FOR THE FARMER AND THE ENVIRONMENT

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ABSTRACT

Crop technology has resulted in dramatic increases in the production of wheat and other crops over the last thirty years. Plant breeding, pesticides, increased nitrogen usage and more efficient farm machinery have allowed North European farmers to improve their competitiveness compared with farmers from traditional wheat exporting countries. However, the rate of yield increase is slowing at a time when there is growing concern over meeting the future demand for food from a rapidly increasing world population. Effective exploitation of current technologies and the uptake of new technologies is required to provide the North European farmer with the flexibility to meet the projected increases in demand for food in a more liberalised market, whilst also optimising inputs of energy, pesticides and nitrogen and responding to public demands to reduce the environmental impact of farming.

INTRODUCTION

Concerns were expressed in the early 1960s that the projected increase in the world population would lead to an expansion in the demand for food which could not be satisfied by agricultural production (FAO, 1962). However, the subsequent rapid increase in food production led to surpluses in the developed world. This rapid increase in production was made possible by institutional support for agriculture, initially to ensure sufficient food production, but latterly to support rural communities. Research and development enabled a dramatic increase in production from crop plants based on the introduction of new cultivars, pesticides, the increased use of fertilisers, soil drainage and improved machinery. The resulting changes in production methods and food surpluses in the developed world caused conflict between farmers, tax-payers and governments. To maximise income, farmers found it necessary to maximise economic production, much of which was supported by the tax-payer rather than the market, using methods which caused changes to the landscape, leading to habitat loss and fragmentation, and real or perceived pollution.

Much of the technology which delivered increased production has now been exploited to such an extent that yield increases are slowing to a rate commensurate with increases in the world population. The spectre of future food shortages has now returned to the agenda. More effective exploitation of recently developed technology and encouragement for more research and development will improve our capacity to meet future demands for food.

There is an implied assumption that the demand for ever increasing production will be met by using methods which will cause equal or increased environmental effects compared to current systems (Holdgate, 1995), which in themselves are unsustainable both from a wider environmental perspective and from an agricultural point of view. There is little evidence in the UK that modern farming systems are unsustainable from a purely agricultural point of view (Tait & Pitkin, 1995). This paper, using as an example the basic food of cereal grains, particularly wheat, sets out to show that future demands for food may be met using methods more in sympathy with the aims and ideals of the general public.

WHEAT YIELDS

Wheat yields increased, particularly in Northern Europe, during the 1970s and early 1980s due to technological developments allowing farmers to exploit further climate and soils favourable to wheat production (Silvey, 1994). This is in contrast to countries such as the USA (Figure 1), Canada and Australia where drought limits yield potential and hence the response to most inputs.

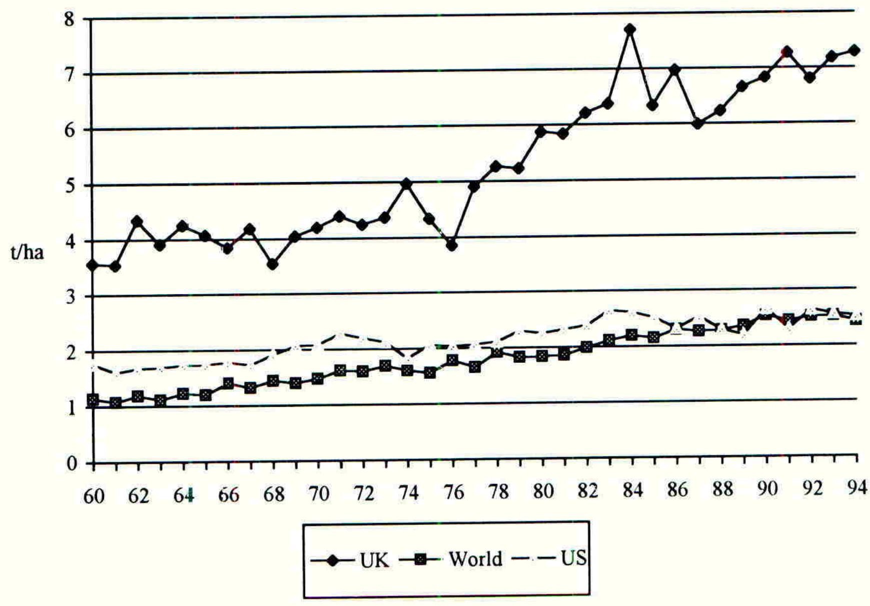

Figure 1. Wheat yields between 1960 and 1994 in t/ha (Source: USDA)

It is disturbing to note, at a time when world wheat stocks are low, that the annual rate of increase in the yield of wheat has slowed over the last four or five years (Figure 1) to a level approaching the projected annual rate of world population growth of around 1.33% (United Nations, 1993). This may be due to a variety of reasons, including production approaching the limits which can be supported by soils and climate and which can be achieved with current technology.

The theoretical maximum productivity for C_3 plants, such as cereals, in temperate conditions is currently estimated as 33 t/ha/year of dry matter of roots and all above ground production (Anon, 1991). In the UK, the best winter wheat crops achieve around two thirds and the average crop about half this maximum. Hence, theoretically there is potential for increased yields in temperate regions but they will, of course, be increasingly hard to achieve as the maximum comes closer.

There is also potential for food production from land set-aside from arable cropping throughout the world and from further yield improvements in Eastern Europe. However, even when this is taken into account, there is still a need for an increase in the world average yield of all cereal grains (Anderson, 1995). Yield increases may have to be proportionally higher in temperate regions, such as Northern Europe, as much of the world wheat production is limited by drought.

The role of pesticides and nitrogen in the enhancement of yields and competitiveness of wheat production in Northern Europe has been described by Orson (1995). Herbicides have minimised weed competition, making possible earlier drilling and non-plough tillage and allowing the flexibility to increase the area devoted to wheat, particularly on the land most suited to its production. Fungicides have protected the crop from foliage diseases and eyespot (*Pseudocercosporella herpotrichoides*) and insecticides have protected the crop from aphid transmitted viruses and the direct feeding of aphids, and have controlled insects and molluscs in the soil. Nitrogen use has increased in order to exploit fully the higher yield potential of the new cultivars protected by pesticides. The rapid increase in yields diluted total costs leading to a fall in the unit cost of production, i.e. the cost of producing a tonne of grain. This, in conjunction with a fall in the value of sterling, has resulted in the UK grower now having unit costs of production similar to those in the USA. The increased productivity through higher yields and increases in labour productivity has enabled farmers to respond to the long-term decline in the price of wheat in the UK (Figure 2).

ENVIRONMENTAL IMPACT OF CROP PRODUCTION

The intensification of production, i.e. increasing the area devoted to a narrower range of arable crops in specific areas or on specific soil types through using optimal inputs of fertilisers and pesticides, has resulted in landscape change, particularly habitat loss and fragmentation leading to a decline in biodiversity and in an increased risk of pollution.

Landscape change has arisen, through changes in land use and through farmers amalgamating fields to increase labour productivity. Biodiversity has declined in association with these changes. Herbicides have reduced the biodiversity of cereal fields through controlling arable weeds, some of which are classified as rare plants, with a concomitant impact on arthropods which feature in the diet of many birds for example. In addition, spray drift may have resulted in a reduction in the biodiversity of crop margins and adjacent habitats. Seed cleaning has also been responsible for reducing the number of weeds, particularly of some species. The reduction in the numbers of some bird and mammal species has been attributed to the reduction of arable weeds (Cooke & Burn, 1995). However, the major effect of herbicides has been to facilitate more intensive arable farming with a consequential effect on biodiversity.

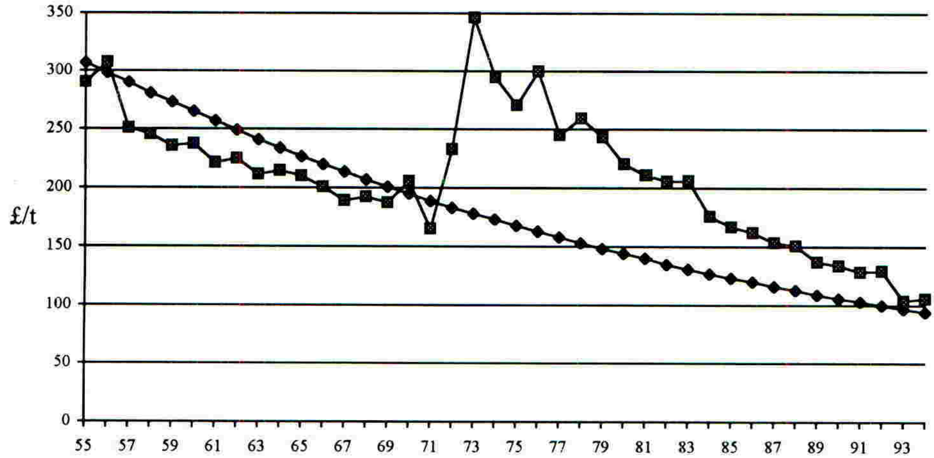

Figure 2. UK average annual wheat price 1955-1994 at 1993 purchasing power, compared to a 3%/annum decline. (Source: Plant Breeding International Cambridge)

Habitat fragmentation may impede movement of wildlife and, by breaking habitats into smaller areas, result in a reduction in their value for certain species. Sensitive species are likely to become rarer through density reduction, range restriction or the concentration of the local population into smaller remnant areas and, with species with limited dispersal, this can lead to population isolation. Normally a decrease in fragment area and increase in isolation leads to a decrease in species diversity (Hill, 1994). However, where the change in land use leads to increased landscape heterogeneity, increases in wildlife diversity may result from an increase in the edge effects between habitats.

Herbicides are found in water in the UK, usually at barely detectable levels (Ashby-Crane *et al.*, 1994). EC directives have resulted in changes in use and registration of herbicides, notably atrazine and simazine. The UK Advisory Committee for Pesticides has recently made recommendations for changes in the use of isoproturon following its frequent detection in water. This herbicide is used very widely in winter cereals for the control of annual grasses and was one of the key herbicides which allowed farmers to intensify winter cereal production on heavy land. The effect of herbicides in water on the flora and fauna of ditches, streams and rivers has not been adequately studied (Cooke & Burn, 1995). Indirectly, by allowing more intensive arable production, herbicides have encouraged greater nitrogen and phosphate usage, contributing to the pollution of water courses with these nutrients.

CHALLENGES OF THE FUTURE

Agriculture has to face up to significant challenges in the future. Most of the population growth is predicted to be in the currently less well developed countries (United Nations, 1993). It is also predicted that their prospective economic development will result in changes in diet and the creation of demand for food from other countries, including the more developed countries (Anderson, 1995). There is currently a burgeoning demand for wheat from China and the Pacific Rim.

Population growth, meeting the changing demand for food types and environmental pressures are not the only challenges. The impact of climate change on food production is uncertain and there could be increased demand for land for non-food crops, for example for biomass crops to produce energy.

It is only when food production is assured that governments can have the luxury to support financially farming methods which do not fully exploit the maximum sustainable production of the land, although there may be overriding reasons to encourage alternative land use to meet specific objectives in some areas.

Current and future world trade agreements are likely to result in increased international competition, particularly in years when food supply exceeds demand. This also suggests that the quest to minimise unit costs of production through optimising yields and the minimisation of input costs will continue.

Currently in the UK, a rotational approach to cropping facilitates minimising the unit costs of production of combinable crops. However, some of the crops grown in such rotations are heavily supported (Table 1). In a more liberal trading regime these rotations may be difficult to sustain. This would suggest that there could be a further intensification of wheat production in the UK, provided that herbicides are developed which will control the resultant specific weed problems. Cropping sequences will have to be flexible to take advantage of the volatile price movements which are predicted in a more liberal market. Therefore, it would be foolhardy to rely entirely on rotations helping to deliver the reductions in inputs needed to meet both the likely economic pressures and the environmental standards of the future. We must look to technological development to provide the flexibility for UK agriculture to be both competitive and sustainable whilst meeting the environmental standards expected of any modern industry.

Much of the environmental impact from farming has been associated with change in land use. It may be possible that in the future productivity improvements will enable land being released from intensive food production for environmental purposes or for non-food production. It is clear that there needs to be diversity in the location, scale and management of this land to meet the requirement to increase biodiversity in the countryside. Managing relatively small areas for specific objectives should continue, although the case for wildlife corridors within intensively farmed land has still to be proven (Hill *et al.*, 1995). Relatively large tracts of land managed through extensive pastoral systems are desirable for some species (Hill *et al.*, 1995). Research is required to ensure that the land released from full production is located and managed in such a way as to maximise its contribution to the environment.

Table 1. Arable crops support payments as a % of 1995 projected average gross margins for England.

	Gross margin (£/ha)	Support payments* (£/ha)	Support as a % of gross margin
Winter wheat	850	269	31.6
Winter barley	700	269	38.4
Winter oats	700	269	38.4
Winter oilseed rape	740	452**	61.1
Dry peas	560	389	69.5
Winter field beans	580	389	67.1
Linseed	640	520	81.3

* Support calculated at 1 July 1995 exchange rate of 1 Ecu = £0.840997 and rounded to the nearest whole £/ha.

** Assumes 5% reduction due to higher average market price. Assumes there will be no area overshoot penalty.

MEETING THE CHALLENGES OF THE FUTURE

It is not possible in this paper to list every technology which will allow crop production to meet the challenges of the future nor to describe them in detail. The following sections discuss the potential for future developments in crop protection, particularly in relation to weed control in cereals.

Current research into matching inputs to crop requirement

Pesticides are regularly applied below the dose recommended on the label. Sometimes this may result in higher margins but this is not guaranteed. Research has resulted in the reduction of the dose used of some herbicides (Cooke & Burn, 1995) whilst still achieving effective weed control. Research is now in progress which will not only improve prediction of the potential damage from weeds, pests and diseases but will also define the appropriate dose of the pesticide to maximise margins. This requires knowledge of the activity of the pesticide, of the impact of weather on its efficacy and of how the target weeds, diseases and pests may affect individual crops. It may also be possible to predict the dose of a specific herbicide which will result in the survival of an uncompetitive number of plants of species which are either relatively uncommon or are important for wildlife.

Decision making will become increasingly complex and it is envisaged that in the future farms will be larger, with less management time available to take decisions on individual crops (Orson *et al.*, 1994). Hence, there will be a need for methods to help the decision maker to reduce inputs through the exploitation of knowledge. Decision support systems are being developed which provide options for farmers or their advisers to consider in the context of individual circumstances and to improve the exploitation of the 'knowledge resource' (Anderson, 1995).

Spatial application of inputs

There is little doubt that information technology will have a significant role to play in the management of crops as well as in the decision making process. Spatial application has opened our eyes to the potential, with further applications under development.

At present, whole fields are usually treated with a single dose of herbicide. The dose is generally influenced by the number of weeds in the patches where infestations are high. Weed maps may allow the farmer to vary the dose of one herbicide or use a low 'background dose' of a herbicide with the application of an additional herbicide in specific parts of a field. Weed patches are relatively stable and can be entered into an electronic map of the field. Whether the process will provide worthwhile economic benefit will depend on the size, distribution and number of patches which are deemed to require separate treatment. The latter will depend on whether all weed species are being treated as one or whether each species or group of species is considered separately. Some separation of species is necessary, particularly between perennial weeds (which can often be mapped at harvest) and annual weeds. It is not sufficient to treat the precise area of the weed patch; there will always be a need to treat a buffer area around the patch to allow for navigation and detection errors and the movement of seed by farm practices. Such an approach may be used to ensure the survival of rare weeds which may be present in a small part of the field or to ensure the survival of weeds which are important from a wildlife point of view in parts of the field where their numbers do not pose a threat to current and future crops.

Plant scale crop protection

New technology can take images from a video camera mounted on the front of farm machinery to identify crop rows and individual plants within and outside the crop rows. Such images can be used to steer vehicles. This opens up the potential for targeting inputs to individual plants or small groups of plants. It also may make feasible effective inter-row weeding in combinable crops. Currently, mechanical weed control in these crops is not successful because both crop and weeds are 'treated' and the level of soil and weed disturbance has to be limited because of the potential for crop damage. Where inter-row weeding is adopted, the crop rows could be protected from weeds through dressing the seed with herbicides or targeting herbicide application within the row. Further advances may make it possible to locate weeds occurring between rows and to respond by applying the appropriate rate of herbicide from individual nozzles or groups of nozzles.

Concerns are frequently expressed about the environmental impact of herbicides (Cooke & Burn, 1995). However, it should be recognised that mechanical weeding may also have environmental consequences. There are likely to be direct effects on fauna on, or close to, the soil surface in addition to ground nesting birds and small mammals. Protecting the crop rows with herbicides and using mechanical weeding to control weeds between the row may be a more environmentally desirable approach, particularly when the crop is sown in bands. Mechanical weeding is not selective and will control both desirable and undesirable weeds. It may eventually be possible, through image analysis, to weed selectively on an area basis. However, the machinery would have to be very refined to achieve the necessary precision.

Pesticides

There is a constant demand for new pesticides to improve the control of organisms, to overcome or reduce the threat from pesticide resistance and to reduce the environmental impact of intensive farming. In the scenario of a further intensification of crops on the land most suited to their production, there is a particular need to improve the control of soil-borne root diseases to provide the farmer with more flexibility in crop rotations.

There is also a particular need for effective herbicides which selectively control bromes (*Bromus* spp.) and herbicide resistant black-grass (*Alopecurus myosuroides*) in winter cereals. Concern over these two weeds often prevents the intensification of winter wheat production and also prevents the adoption of non-plough tillage to reduce cultivation costs and energy use on heavy soils.

Biotechnology

There is a massive investment in biotechnology by multinational companies, venture capital funds and government supported research programmes and it is difficult to predict the outcome. For instance it may result in more drought tolerant crops, increasing the competitiveness of cereal production in countries such as the USA, Canada and Australia. It may also allow cereals to meet more exactly the specific quality characteristics demanded by major or niche markets and, in addition, the introduction of cheaply produced hybrid cereal seed leading to higher yields. Hybrid vigour may also result in lower inputs of fungicides and nitrogen into cereals.

The implications of the introduction of crops genetically modified to be resistant to more environmentally benign, non-selective herbicides is currently being debated in the industry. There are obvious advantages in the control of volunteers of the same species and of weeds, some of which may have developed resistance to selective herbicides. However, there are concerns amongst farmers about the long term implications, including the consequences of the herbicide resistant gene being released into the environment, the control of volunteers of herbicide-resistant crops and herbicide availability for minor crops. It is clear that each introduction should be judged on its own merits. For instance, volunteers of some crops are poorly controlled by some non-selective herbicides and hence the introduction of cultivars modified to be resistant to a non-selective herbicide will not necessarily increase the problems of weed control between crops. This statement is subject to the assumption that the competitiveness and field characteristics are the same for the volunteers from conventional crops and genetically modified herbicide-resistant crops.

CONCLUSIONS

Crop technology has assisted farmers, particularly those in Northern Europe, to increase production rapidly over the last twenty years. Further exploitation of current technology and adopting new technology are absolutely essential to provide the flexibility to meet the future challenges of a more liberalised trading environment, the increase in world population and rising environmental standards. Individual technologies will be integrated with the best of current practice to provide the flexibility for individual farmers to maximise margins and minimise unit costs of production whilst meeting more exacting market requirements and environmental standards. These environmental standards may be met by optimising inputs of energy, fertilisers and pesticides, producing higher yields and thus making it more likely that land can be released to meet specific environmental objectives and also by continuing with best current practice in the choice of pesticides combined with specific measures for crop, field margin and landscape management.

To ensure that current and future technology is effectively transferred to field practice there needs to be an increased emphasis on the fuller exploitation of the knowledge resource. This was done in the past by government extension services giving free advice. With the withdrawal of government from this activity, alternative methods will have to be developed. There is little doubt that information technology will play a crucial role in the effective technology transfer to farmers and their advisers in order that they meet the considerable challenges of the future.

It is likely that the challenges of the future and the response of the industry to those challenges will result in more commonality in the objectives of farmers, governments and the tax-payer. Hence, there should be less conflict for an industry which provides one of the basic needs: feeding the world's population.

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