Weed Management Handbook

Ninth Edition

Edited by

Robert E.L. Naylor
Trelareg Consultants
Finzean, Banchory, Scotland

Published for the British Crop Protection Council
by Blackwell Science

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Introduction

The first edition of the *Weed Control Handbook* appeared in 1958 and the eighth edition in 1990. Weed control has changed since the last edition. New ideas, information and understanding have been incorporated into weed management systems. More importantly, new weed management challenges are presenting themselves and need to be addressed.

In previous editions the subject has been divided into two areas and the *Handbook* was issued in two volumes: Principles and Practice. For this edition it has been decided to merge the two areas into one volume. This more effectively demonstrates the linkage of knowledge and information with weed management practice. As we have learnt more, so we have evolved our weed management systems to be both more effective and at the same time less harmful to the environment.

The change in title from *Weed Control Handbook* to *Weed Management Handbook* is a deliberate one. The emphasis in cropping systems is now much less on production. Agricultural policy at EU, UK and regional scales now pays far more attention to producing food in a sustainable and ethical manner. Agenda 2000, the main agricultural policy instrument of the EU, makes the environment more central to agricultural policy. The policy states '...The integration of environmental goals into the CAP and the development of the role farmers can and should play in terms of management of natural resources and landscape conservation are increasingly important objectives for the CAP...'. Clearly, the objectives of arable cropping are influenced by this and indeed the role of farmers is changing to one of countryside managers. The former UK Ministry of Agriculture, Fisheries and Food (MAFF; now the Department for Environment, Food and Rural Affairs, DEFRA) has evaluated the effects of the revised agreement on Agenda 2000 made at the Berlin Heads of Government meeting in March 1999. MAFF estimated that the UK arable sector would lose £180 million. Relative to other countries in the EU, the package was estimated to make wheat more profitable in the UK, but protein crops and oil crops less profitable.

Clearly, this influences which crops are grown and also signals that the central feature of cropping systems will be to drive down costs of production. Growers can achieve this through the use of both biotechnology and non-biotechnology. On the non-biotechnology front, the focus is to achieve greater efficiency of utilisation of resources. Knowledge and information technology have a role in providing better decision making while engineering solutions can achieve greater efficiency through, for example, more accurate and localised placement of fertilisers and agrochemicals. On the biotechnology front, the attractiveness of many of the new cultivars (conventional or genetically modified) that are becoming available is that they lead to easier and cheaper crop protection.

At the same time, the regulation of activity on farms is increasing. The requirement of society is that growers achieve production in an environmentally benign way. Thus, crop production is a challenging activity. Increasingly, the decisions made in managing crops have an important financial consequence but the options are constrained. This is particularly so in the field of crop protection, where a high proportion of compounds will cease to be registered and will therefore not be available for use.

This book comprises a series of chapters written by experts in their field, in a sequence that reflects a progression from the biology of weeds, through the underpinning science and technology relating to herbicides, to principles of weed management techniques and finally a set of 'case studies', describing the main options available. There is more emphasis than in previous *Handbooks* on techniques to reduce the application of herbicides through the incorporation of mechanical and biological methods of weed management into what can be termed 'integrated weed management'.

Weed scientists and technologists interact greatly with each other and all have a clear focus on the question of how we limit weed populations in crop fields (and elsewhere). The authors in this book have illustrated the links between the various disciplines and subject areas that contribute to 'weed management'. Inevitably, this means that there is a degree of overlap and cross-reference between the chapters. As editor, I have not tried to limit this overlap because the links are important; weed management decisions must be based on as complete a knowledge and information set as possible if the decisions are to be sound and effective. Occasionally readers will notice differences of interpretation between authors. Again, I have not tried to impose a uniform view, as the open discussion of such issues is healthy for the subject because it exposes our ignorance and identifies where we need further research or development.

Weed management does not stand still and it is not the same as it was ten years ago. Nor will it be the same in ten years' time when new weed problems will have arisen in response to changes in cropping systems. Different management systems will be developed to deal with these. The new management systems will have to conform to the demand of society for solutions which are at least environmentally benign or, better, lead to enhancement of the countryside for all to enjoy. At the same time the new solutions have to be cost-effective in a tighter financial climate.

I thank all the contributors for the time and effort they have devoted to writing their chapters. Without them, there would be no *Handbook!* I also thank BCPC for their foresight in producing a new edition and their trust in asking me to edit it. The weed science community is small but active and I am sure an updated version will be needed in another ten years to take account of the new knowledge about weeds and the fresh technology that can be brought to bear on managing weeds. The poet Gerald Manley Hopkins said ‘Long live the weeds…’ (Inversnaid). We need to add ‘long live the weed scientists’!

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Chapter 1
What is a Weed?

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Synopsis

What is a weed? Why is it a weed? What features of its biology make it a weed? This chapter is concerned with answering these questions, and with the way in which knowledge of weed biology helps to devise weed management strategies.

Definitions

There have been numerous definitions of weeds. Older ones include ‘a plant not valued for its use or beauty’ and ‘a plant whose virtues have yet to be discovered’. However, most modern definitions convey an opinion that the plants are considered undesirable in some way. This is reflected in the German term *unkraut* and the French *malherbe*. A great variety of reasons can account for a plant being unwanted but most encompass a view that the plant is a nuisance and in some way hinders or interferes with human activity. This leads to the understanding that crops may at some time also be weeds. For example, the grass plants growing in the domestic garden lawn are acceptable and encouraged, but when they spread to the adjacent flowerbed they are considered weeds. Similarly, crop seeds which are shed in the field can grow in subsequent crops in following years and contaminate them. The definition of weeds adopted by the European Weed Science Society is ‘any plant or vegetation, excluding fungi, interfering with the objectives or requirements of people’. Similarly the Weed Science Society of America has adopted the definition ‘a plant growing where it is not desired’.

Reasons for classifying a plant as a weed

The definitions above emphasise that there is nothing special about the biology of weed plants but they merely have to interfere with the activity of humans. We generally think of weeds as being a nuisance because they interfere with agricultural activities, but Table 1.1 summarises some of the other reasons for

Table 1.1 Reasons for calling a plant a weed

Justification	Mechanism	Examples
Reduce crop yield	Interference with access to plant growth resources of light, water and nutrients	*Avena fatua, Galium aparine* in cereals, *Poa annua* in grassland
Reduce crop quality	Admixture of contaminating seeds in arable crops	*Sinapis arvensis* in oilseed rape
	Contamination of vegetable crops	*Solanum nigrum* berries in peas
Delay harvesting	Conservation of moisture may delay ripening and increase crop moisture level when harvested	*Matricaria* spp. in oilseed rape
Interfere with harvesting	Climbing plants make combine operation more difficult	*Fallopia convolvulus*
	Vigorous late-growing weeds can interfere with harvesting potatoes and sugar beet	*Chenopodium album*
Interfere with animal feeding	Plants with spines or thorns inhibit animal foraging	*Cirsium arvense*
Cause poisoning		*Senecio jacobaea,* *Digitalis purpurea,* *Laburnum anagyroides,* *Rhododendron ponticum*
Taint animal products	Impart undesirable flavour, e.g. to milk	*Allium ursinum,* *Ranunculus* spp.
Act as plant parasites		*Cuscuta* spp.
Reduce crop health	Act as alternate or alternative hosts for crop pests and diseases	Cruciferous plants harbour clubroot; many grasses harbour ergot of cereals
	Increased vegetation at base of crop increases moisture level and levels of disease	Weeds in oilseed rape can increase levels of *Botrytis*
Reduce animal (and human) health	Act as intermediate hosts or a vehicle for ingestion of pests and parasites	Grass
	Photosensitisation	*Hypericum perforatum*
	Teratogens	*Pteridium aquilinum*
Are a safety hazard	Reduced vision on roadsides	Tall plants
	Fire risk under electricity lines	Any plants, but especially scrub

Contd.

Table 1.1 *Contd.*

Justification	Mechanism	Examples
Reduce wool quality	Hooked seeds reduce value of fleeces	*Bidens* spp.
Prevent water flow	Plant mass blocks ditches and irrigation channels	*Elodea canadensis*
Exhibit allelopathy	Release of substances toxic to crop plants	Little evidence this occurs in the field in northern European agriculture but it may be relevant in tropical conditions
Impact on crop establishment	Vegetation prevents establishment of young trees	

considering plants to be weeds and therefore for managing their occurrence. The examples given are from northern Europe, and are considered in more detail below.

Reduction of crop yield is the major reason for attempts to reduce weed populations in arable crops, but effects on crop quality are almost as important for horticultural crops. The first attempts at controlling weeds used manual labour and hand-pulling or hand-hoeing. A major advance was the mechanisation of the process, permitting a greater area to be covered in a day. The technology required the development of a machine to sow the crop in rows so that the weeds in the spaces between the rows could be easily removed by an implement drawn behind a power source (animal or mechanical). This was the main method of weed management from the early 19th century up to the middle of the 20th century in developed countries and is still practised successfully today, around the world.

A major revolution was the development of herbicides in Britain, the USA and Switzerland. The ability to reduce weed populations growing in crops has been an important component of the increased food production by western agriculture. The recorded increases in crop yields in the UK over the 50 years since 1940, of 1 tonne every ten years (Fig. 1.1), contain contributions from a number of sources, including improved varieties of higher potential yield, improved crop nutrition and improvements in all aspects of crop health, including weeds. In trials, unweeded control plots provide a comparison with plots on which the weed population has been severely reduced (Fig. 1.2). Clearly the impact of weeds on crop yield can be considerable, or more accurately, some weed species have a large impact on crop production. This leads to consideration of the relative impact of different weed species which then allows the prioritisation of weed management options. The most important weed species which have the largest

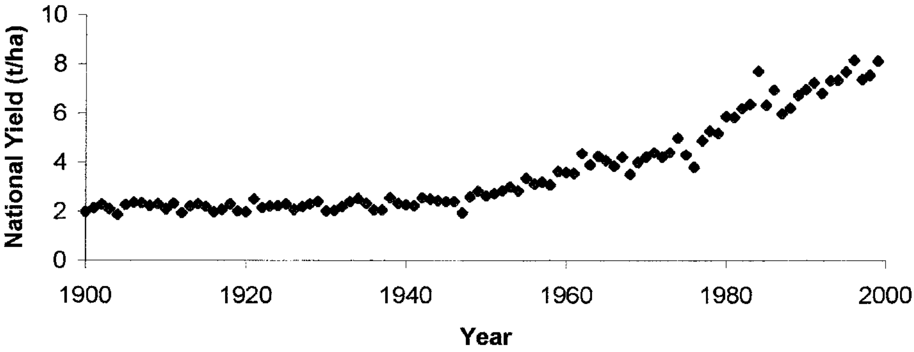

Fig. 1.1 Trends in UK wheat yields in the 20th century.

impact on crop yields in northern Europe are given in Table 1.2. In organic systems, where herbicides cannot be used, management of weeds is of greater concern than management of pests and diseases. In conventional systems, the spend on herbicides in the UK is nearly half the spend on all agrochemicals.

Investigations into how weeds achieve the reduction of crop yield show that shading can often account for much of the effect. This is particularly important when the weed seedlings emerge at the same time as, or earlier than, the crop because then the weed has the opportunity to intercept more light and shade the crop. Selection of crop species has tended to favour those lines which emerge early and show rapid seedling growth, because then the crop will shade the weed. The earliness of complete crop ground cover used to be an important feature of

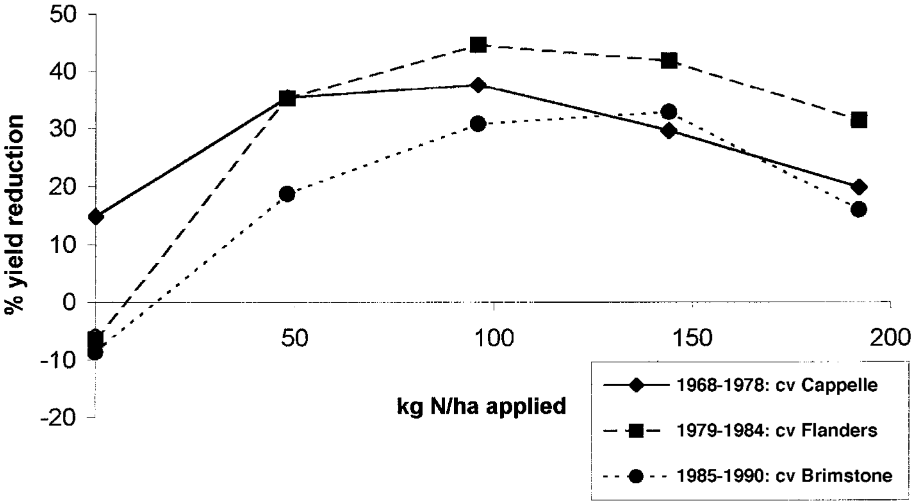

Fig. 1.2 Yield loss (%) on weedy plots of continuous winter wheat crops compared to adjacent weed-free plots for three varieties of wheat (data for 1968–1990).

Table 1.2 Europe's worst weeds: the results of an informal survey of weed specialists in December 2001*

Weed species[†]	Country[‡]	Main crops affected	Herbicide resistance
Grass weeds			
Alopecurus myosuroides	Fr, Ge, GB, Sw	winter cereals	yes
Apera spica-venti	De, Ge	cereals	yes
Avena spp.	Es, Fi, GB, Hu, Sw	cereals	yes
Cynodon dactylon	Es	vineyards, orchards	
Cyperus spp.	Es	irrigated crops	
Echinochloa crus-galli	Nl	maize	
Lolium spp.	Es, Fr, It	cereals	yes
Sorghum halepense	Hu	cotton, soya, maize	
Annual broad-leaved weeds			
Chenopodium album	Fi, Nl,	spring crops	
Conyza canadensis	It	perennial and annual crops, non-cropped land	
Galium aparine	De, Fr, Ge, GB, Sw	many crops	
Polygonum spp.	Nl	spring crops	
Solanum nigrum	It, Nl	vegetable crops	yes
Stellaria media	De, GB, Nl	many crops	yes
Xanthium spp.	Hu, It	cotton, soyabeans, maize, sunflower	
Perennial broad-leaved weeds			
Convolvulus arvensis	Hu	cereals	
Elytrigia repens	De, Fi, Ge	many crops	
Rumex obtusifolius	Sw	grassland	
Sonchus/Cirsium spp.	De, Fi, Fr, Nl	many crops	

* Individuals were asked to identify the most widespread species and/or those most difficult to manage as well as whether herbicide-resistant populations existed.

[†] *Avena* spp. = *A. fatua, A. sterilis* spp. *ludoviciana.*
Sonchus/Cirsium = *S. arvensis, C. arvense* (perennial thistle species).
Polygonum spp. = e.g. *P. aviculare, P. persicaria, Bilderdykia convolvulus.*
Xanthium spp. = mainly *X. strumarium.*
Lolium spp. = *L. rigidum, L. multiflorum, L. perenne.*

[‡] Countries: De = Denmark, Es = Spain, Fi = Finland, Fr = France, Ge = Germany, GB = Great Britain (but mainly England), Hu = Hungary, It = Italy, Nl = The Netherlands, Sw = Switzerland.

husbandry which is receiving increased attention now that the desire is to minimise herbicide applications.

Weeds may also interfere with the below-ground functioning of crop plants. Uptake of water and of nutrients by weeds represents the use of resources which we would prefer to be incorporated into crop plants. Recent research indicates that the roots of many weeds are concentrated in the surface layers of the soil, in contrast to more deeply rooted crop species. This gives the weeds an advantage when scavenging for fertilisers but puts them at a disadvantage when water is limiting.

For many years plant breeders, especially those working with cereals, have ignored the ability of their crops to compete with weeds, and as a result have developed cultivars that have erect leaves that are good at trapping radiation but not good at shading lower-growing plants (weeds). However, there is now some interest in the identification of cultivars which are more suppressive of weeds or at least tolerate their presence better. Such so-called 'competitive varieties' are an important contribution to the development of organic systems in which herbicides are not used.

Until the introduction of statutory seed testing, a major means of spreading weeds was with crop seeds. Now, the seeds of crops traded internationally must meet minimum quality standards of purity as defined by either ISTA (International Seed Testing Association) or AOSA (Association of Official Seed Analysts). Despite these regulations, seeds of many weed species still occur in crop seed samples (Table 1.3), and of course there is no check on farm-saved seeds. Transport of straw can also move weed seeds from farm to farm.

Table 1.3 Percentage of samples of wheat, barley and oats submitted for testing at the Scottish Seed Testing Station which contained weed seeds (*from information in Don, 1997)*

	Wheat	Barley	Oats
1986–1987	36	29	70
1991–1992	51	33	60
1996–1997	38	28	73

The presence of a large volume of weeds in a crop canopy can alter the water relations of the crop. This may be particularly important where the product is a seed and needs to be harvested relatively dry (e.g. cereals, oilseed rape). The mat of weeds transpiring in the canopy can reduce the loss of water and hence delay crop seed ripening. Such a delay may make harvesting riskier. In addition, the presence of weeds can make the operation of harvesting machinery more difficult and slower, particularly when climbing or choking weeds are present.

In grassland, the presence of weeds can present problems additional to the reduction of forage yield. Spiny species such as thistles may inhibit animals from utilising the pasture species in their immediate vicinity. Some species, such as ragwort (*Senecio jacobea*) are poisonous. Although most stock avoid the growing ragwort plants, when incorporated into hay or silage these plants still maintain their poisonous properties although they are dead. Stock are unable to avoid the plants in such circumstances. Most buttercup species are poisonous if consumed to excess. The presence of some aromatic species, e.g. wild species of garlic (*Allium* spp.) in forage may lead to milk becoming tainted.

The effect of weeds on human activities may not be direct. Many wild species act as hosts for crop pests and diseases. Many cruciferous weeds (related to oilseed rape, sprouts, cabbages etc.) are also susceptible to the same diseases, e.g.

clubroot (*Plasmodiophora brassicae*), and can therefore be described as alternative hosts. An important part of the control strategy for this disease is to avoid planting brassica crops in the same location for the following five years. However, the presence of weeds of the same family may allow the pathogen to maintain high inoculum levels. The common chickweed (*Stellaria media*) is the source of mosaic virus for a number of crop species. Many weed species harbour nematodes which may infect crop species and cause significant yield loss. The weed fat hen (*Chenopodium album*) is a host for the black bean aphid which damages broad and field beans. Some plant diseases require more than one species as hosts at different stages in the life cycle. It is important to reduce the occurrence of such alternate hosts if the disease is to be contained. An example of this is the need to control *Berberis* (barberry bushes) to restrict the sources of the cereal rust *Puccinia graminis*.

Particularly in pasture, plants may act as a source of ingestion of animal parasites. There is not always a specific relationship between the animal disease organism and the plant species; often the grass crop itself is a passive agent leading to ingestion, e.g. of lungworm.

Weed seeds with hooks or spines are often cited as examples of seeds that are dispersed by animals when they become entangled in animal coats, but the presence of such seeds may reduce the value of the fleeces and thus lead to a desire to reduce the occurrence of that species in pasture.

It should be clear that the definition of a weed is not just related to agricultural situations. Tall plants which grow on roadside verges may obscure motorists' vision. This creates a need to manage the vegetation height, usually by mowing. Similarly, scrub species growing beneath power lines may create a fire hazard and require control. The tall vegetation along railway lines was a distinct fire hazard in the age of steam trains, when sparks from the smoke stack could set vegetation alight.

Aquatic plants can be a nuisance where their growth impedes the flow of water in drainage ditches or irrigation channels. An example in Europe is Canadian pondweed (*Elodea canadensis*), while worldwide the water hyacinth (*Eichhornia crassipes*) is particularly troublesome on many lakes and waterways. Introduction of exotic species into aquaria and ornamental ponds (e.g. Canadian pondweed) poses increasing problems resulting from their escape into natural water systems.

It is claimed that the performance of crop species can be reduced by the release of inhibitory chemicals by neighbouring species. This is termed allelopathy. Many laboratory experiments have shown that aqueous plant extracts can reduce crop seed germination. This can be shown by soaking grass clippings from the lawn in water for 24 hours, and using the filtrate to water seeds of any crop species in a germination test in petri dishes. Fortunately for the grower, in many situations the effect disappears when the same experiment is modified by applying the filtrate to soil in which the seeds have been sown. There is thus serious doubt as to whether allelopathy can account for any yield reductions of crops in the field in northern European conditions. However, there is increasing evidence that allelopathy can play a role in crop–weed interactions in warmer and wetter tropical growing conditions.

Pride is a very major influence in deciding on weed control because growers want their own crops to look cleaner than their neighbours'. Anecdotal evidence suggests that about half of all herbicide applications may not be economically justified and therefore lead only to cosmetic benefits. However, financial pressures are forcing a re-evaluation of all the components of a crop management system and the proportion of cosmetic applications should decrease.

Beneficial effects of weeds

It seems paradoxical that weeds may be also be considered valuable. Part of the resolution of the paradox is in the definition of a weed as a plant out of place. Clearly, in the right place, a plant species may have properties which are beneficial to man or his activities.

The man-managed arable and grassland areas of Europe generally have a reduced diversity of flora and fauna. Reduced biodiversity has been used as a measure of the intensity of management. Current EU policy is to encourage farmland biodiversity through less intensive farming, achieved either by reducing the intensity of management overall or by reducing the managed area. Weeds are perceived as valuable indicators of biodiversity because of their role in providing food or shelter for animal species. Much of the decline in farmland birds has been linked to the reduction of weed occurrence in arable crops. The rarer farmland birds can be encouraged to visit and to breed by accepting a certain level of weeds in a crop. A delay in weed management activities may permit chicks to be reared before the food supply is removed, and weeds in stubbles can provide some winter feed. Weedy strips are planted to encourage cover for game birds. While birds are particularly prominent and well recorded, the same arguments can be used for other, less well-studied organisms.

Rotational grassland is very dependent on relatively few species of grasses, especially *Lolium* (ryegrass) and *Festuca* (fescue) species. The seed mixtures sown now contain only a small number of species of grasses, sometimes with red or white clover, and are very different from the seed mixtures sown in the first half of the 20th century. A typical mixture then might have contained additional species of grasses (e.g. *Phleum pratense*, *Dactylis glomerata*, *Poa trivialis*, *Cynosurus cristatus*), legumes (e.g. *Trifolium incarnatum*, *Onobrychis viciifolia*, *Anthyllis vulneraria*) and many other species which were included to improve the mineral nutrition of the sward (e.g. *Achillea millefolium*, *Plantago lanceolata*, *Potentilla anserina*, *Chicorium intybus*, *Symphytum officinale*).

Bare soil is very vulnerable to erosion by wind and water. The presence of a plant cover helps to lessen the momentum of impacting raindrops and the plant roots help to bind the soil to reduce its ability to move.

There is considerable interest in limiting weed management measures to allow populations of beneficial organisms to develop. Insects which pollinate crops (e.g. bumblebees) need a source of nectar and pollen when the crop is not in flower, and weeds can provide this. The natural predators of aphids include ground beetles, spiders and hoverfly larvae. Weed flowers may provide a food source for these natural predators and thereby reduce the reliance on aphicides. Weeds themselves may be more attractive to crop pests; thus aphid infestations on sugar beet in weedy fields have been reported to be lower than those on weed-free crops.

Similarly, intercropping of carrots with clover has been shown to reduce infestations of carrot root fly.

Some weeds may actually be valuable plants happening to grow where we do not want them. Around the world, many wild plants are used as herbs for flavouring, and others are used for their medicinal properties. There is a resurgence of interest in 'herbal' remedies which are perceived as safer than synthesised pharmaceutical drugs even though the latter have undergone a rigid approval process. Many drugs have their origins in plant secondary metabolites, and indeed some are still derived by extraction from plantings of such medicinal plants. Foxglove (*Digitalis purpurea*) is a poisonous plant and a source of the glycosides digitalin and digitoxin, which are used as cardiac stimulants and vasoconstrictors.

Biological features of weeds

What makes an aggressive and successful weed? A species may become a weed because of a chance combination of circumstances that make its attributes particularly advantageous to its growth and survival. For example, during the late 1970s and 1980s the increased use of minimum tillage techniques to establish winter cereals, combined with the absence of rotations, provide a niche that favoured the increase of barren brome (*Anisantha sterilis*) in the UK. This weed remained a serious problem in monocultures of cereals until rotations were re-introduced and ploughing replaced minimum tillage.

One can speculate that certain attributes of plants will predispose them to weediness. Clearly such attributes as high seed production, a short growing season and effective seed dispersal will tend to make a species a successful weed. Further, the species should possess a varied genotype that equips it to accommodate a wide range of environmental conditions. An interesting approach to describing the features of weediness was made by Baker (1965), who tried to define the 'design features' of an 'ideal weed'. For both annuals and perennials, these were:

- The ability to germinate in many environments
- Discontinuous, self-controlled germination and great longevity of seed

- Rapid seedling growth
- Early onset of seed production in a range of environments
- Long period of seed production
- Self-compatibility
- Easy cross-pollination
- High seed output in favourable circumstances
- Some seed production in adverse conditions
- Long and short-distance dispersal
- Special means of competition

and, if perennial:

- Vigorous vegetative reproduction
- Brittleness of lower nodes or rhizomes
- Ability to regenerate from fragments

This list is particularly helpful when considering the potential weediness of new weed species, but the absence of these attributes does not necessarily mean that a species will not become a weed. Indeed, important weeds often possess only a proportion of these attributes. The agricultural ‘environment’ in which the species exists, and the way farmers manage their land, are just as important.

Weed biology

The biology of weeds, as highlighted by ‘Baker’s Rules’, plays a very important role in determining the success of individual species as weeds. This may be due to the behaviour of the seeds, the competitive ability of the plants or their seed production. The biology then interacts with the crop or land management, whether that crop be winter wheat, apples or amenity grassland.

The behaviour of weed seeds is particularly important to the potential of a species to become a weed. One of the earliest observations on the number of seeds in the soil was made by Darwin (1859). He placed mud from a pond in a cup and counted the seedlings emerging over six months. He obtained 537 seedlings from 210 g (dry weight) of mud. The weed seed population (Chapter 3) is frequently large, considerably larger than the typical sowing rates of crop species. The sowing rate of barley is about 3 million seeds/ha: in contrast, seed populations per hectare of poppy species (*Papaver* spp.) have been measured as 279 million, of brome (*Bromus* spp.) as 24 million and of blackgrass (*Alopecurus myosuroides*) as 55 million. Estimates of the total weed seed population in arable soils are usually between 1000 and 10 000 seeds/m^2.

The practical significance of weed seed populations in the soil is that they impose a need for continued weed control over a number of years. This is because not all weed seeds germinate at the same time and because most herbicides do not affect dormant weed seeds. The weed seed bank is the primary method of ensuring the longevity of a plant species and, in agricultural terms, the appearance of new seedlings in future crops. Thus, the numbers of seeds produced and their longevity in the soil are of prime importance. Seeds with short persistence, such as those of barren brome (*Anisantha sterilis*), will have their primary effect on crops grown in the following year, whereas seeds with long persistence, such as poppy (*Papaver rhoeas*), will continue to have the potential to infest new crops for many years. The distribution of seeds is also important, as those with attributes facilitating long-distance transport will have greater potential to infest new areas than those that simply drop their seeds close to the parent plant. The behaviour of seeds is influenced by agricultural practice; for example ploughing tends to increase seed persistence compared to surface cultivation.

The ability of weeds to produce seeds for future generations will depend on the intrinsic productivity of the plant and on its ability to compete with other vegetation, either crops or other wild plants. Some species produce large numbers of small seeds, whilst others produce fewer, large seeds. Both strategies can be successful. Poppy (*Papaver rhoeas,* many small seeds) and wild oats (*Avena fatua,* few large seeds) are both common in agricultural landscapes. Species also differ in their competitive abilities, which is important in relation to their effects on crops but also significant as far as seed production is concerned. A vigorous competitive weed will have an appreciable effect on crop production and is also likely to be successful in producing seeds.

Many of the other components of weed population dynamics (Chapter 4) can affect the success of weeds. However, there is often a close link between the significance of the biology and the crop or land management imposed by farmers. For example, the persistence of volunteer oilseed rape depends on the induction of secondary dormancy in the seeds, which is influenced by the post-harvest cultivation regime used by the farmer. Similarly, the success of cleavers (*Galium aparine*) in winter wheat can depend on the timing of herbicide treatment and the pattern of seedling emergence, which can occur in both autumn and spring.

Interaction between weed biology and crop management

Knowledge of weed biology, particularly in relation to reproduction and to population dynamics, is a necessary prelude to successful weed management. There is a need to balance the detrimental aspects of weed growth against any beneficial aspects, particularly their role as food or hosts for crop pests and diseases against the harbouring of natural predators and food or shelter for valued wildlife (Chapter 5).

In developing weed management strategies and in planning the detailed tactics it is crucial to emphasise the necessity for a long-term approach. Often the strategies will incorporate a sequence of crop management decisions, which may involve the planned use of herbicides but should also incorporate non-chemical methods (Chapter 13). Clearly it is important to prevent the introduction of new weeds, so the cleanliness of seed and reduction of the spread of weed seeds by way of straw, manure or machines are important.

Some weed species can be regarded as indicators of particular soil conditions and therefore attention to ameliorating these conditions has a major role in weed management. For example, the occurrence of spurrey (*Spergula arvensis*) can be taken to indicate an acid soil with low pH, so liming is an important tool for control as well as benefiting the growth of most crops. Similarly perennial sow-thistle (*Sonchus arvensis*) can be taken to indicate poor soil structure and so remedial ploughing, subsoiling or draining may improve crop growth as well as reducing the weed occurrence.

The rotation of crops has an important part to play. The avoidance of continuous cultivation of a field with the same crop is crucial to prevent the selection of a well-adapted weed flora. The use of winter-sown and spring-sown crops, alternating between annual and perennial crops (i.e. including a grass ley which may have other benefits) and alternating between close, dense crops which shade out weeds (oilseed rape, rye) and more open crops (maize, many vegetables), all help in preventing the preponderance of particular species. The variety of crops permits the use of a wider range of herbicides and a variety of soil cultivation methods both before the sowing of the crop and while it is growing. In addition, cutting or topping operations in leys can suppress tall perennials. The choice of soil cultivation technique has an effect in selecting the weeds which survive the disturbance best. Decisions on the use of ploughing versus minimum tillage and the timing of cultivations are important. The time of sowing, the use of cross-drilling and the incorporation of a 'stale seedbed' into the cropping system are all critical.

The selection of competitive varieties of crops can play a role in suppressing the growth of weeds. Currently, few growers of arable crops take this into account when selecting cultivars, apart from those intending to grow crops organically, when the grower needs to optimise all aspects of weed suppression. Of particular importance is the ability of the variety to produce a completely closed crop canopy as early as possible. This can lead to successful suppression of weed growth through shading. Crop species which germinate and establish quickly (e.g. cereals) are notably more suppressive of weeds than others, such as many vegetables, which may take a long time to produce a closed canopy. There are important differences in the earliness and leafiness of different varieties, and the information merits incorporation into the weed management strategy. Crop competitiveness can also be increased by other features of agronomy such as plant nutrition, closer row spacing, higher sowing rates and pre-germination of seeds.

Although it is feasible to develop a weed management strategy for a single farm or individual field, the implementation of the strategy is more difficult because the weather plays an important part in determining the ability to work on the land and to perform particular activities. Thus the strategy will always need to be flexible and incorporate a number of approaches in order to be resilient (see Chapter 14).

The incorporation of biological control of weeds is attractive (Chapter 17). The idea of encouraging natural enemies is sound so long as the introductions are closely confined to the target weed and do not transfer to other species when the target species is reduced to a rare food plant or host. Biological control is expensive to set up but can be cheap to continue. There are relatively few successful examples. The control of prickly pear cactus (*Opuntia* spp.) in Australia has been a major success. There is the possibility of using a moth from southern Africa for bracken (*Pteridium aquilinum*) control in the UK and we are close to controlling musk thistle (*Carduus nutans*) in the USA. Recent advances in biological technology have led to the development of mycoherbicides, i.e. genetically engineered fungi capable of controlling specific weeds.

The options for mechanical control of weeds are many. The grower can decide whether to choose an overall treatment which is usually fairly expensive, as opposed to targeted operations (now using machine vision) for which the equipment is expensive. Nevertheless, there are often other benefits from mechanical weeding, e.g. soil aeration. The difficulties associated with mechanical control are that optimum timing may be difficult because of the weather, and the extra traffic gives risk of soil compaction.

Recent developments have led to the development of thermal weeding, in which heat is used to kill weeds. Flame weeding can be used within the crop row. Its use before crop seedling emergence may indeed hasten the process; it is thus beneficial for slowly emerging crops, and is often used for vegetables.

The development of chemical weed control has been a major success in terms of the additional food production that has resulted. There is much information on the compounds used. We can classify chemicals by usage in terms of:

- where they are applied (e.g. to the foliage or to soil);
- when they are applied (pre-sowing or pre-planting, pre-emergence of seedlings or post-emergence);
- the extent of the application (overall, directed away from the crop or in a band along the crop rows);
- their mode of action (total or selective).

The weed scientist will also consider the selectivity of the compound because this will limit the crops on which it can be used (the action spectrum). How the molecule penetrates the weed plant and its mode of action are both important. After the weeds have died there are serious concerns about herbicide residues, especially their persistence and fate in the soil. Allied to this are the concerns of toxicity to non-target organisms (including humans), hazards and safe usage, and therefore the regulation of herbicide use (Chapter 7). In order to save on application costs, weed management practitioners will want to know whether the compounds can be used in mixtures. Not least, the users will need to be convinced of the benefits in extra yield to be achieved for the cost of the herbicide and its application.

Weeds in the future

The most likely reason for changes in the species occurrence and distribution in agriculture and horticulture is any change in crop management. Current increased interest in early drilling and minimum tillage in winter wheat is already causing increases in grass weed problems, despite the use of stale-seedbeds. The arrival of herbicide-resistant crops, both conventionally bred and genetically modified, could help to solve current, otherwise intractable, weed problems, but may also bring their own difficulties, such as the control of herbicide-resistant volunteer crops. Crops present as weeds in other crops will remain important and the presence of 'added' herbicide resistance genes may make their control more difficult in some situations. The repeated use of single herbicides or single herbicide groups to control certain weeds has been causing increasing problems, due to the selection of resistant biotypes. In Europe the main problems are associated with annual grass weeds resistant to substituted urea herbicides and/or the specific graminicides, but it is likely that grass and broad-leaved weeds resistant to sulfonylureas will become more common, as has already occurred in north America.

It is also possible that climate change may result in the appearance of 'new' weeds from southern Europe, but even here the most likely cause will be a climate-induced change in cropping. If northern Europe starts to grow large areas of grain maize or soybeans, then one would expect the appearance of weeds commonly associated with these crops. However, climate change could impact on weeds in a more subtle way. The occurrence of milder winters could influence emergence patterns in current weed species, changing their vulnerability to control techniques. Changes in climate might also affect the flowering of species requiring vernalisation to produce flowers.

A very different problem with weed management is likely to arise from the withdrawal of many older products from the market (Chapter 18). Although an adequate range of products will be retained for the major crops, more and more smaller-area arable and horticultural crops will be bereft of suitable products. This will mean that integrated approaches to crop management, involving the increased use of physical weed control methods and changes in production systems, will have to be employed (Chapters 13 and 14). This will result in a switch of weed species in these crops, away from those that are difficult to control with herbicides towards those that are difficult to manage with non-chemical techniques. Similarly, the increased interest in Europe in the production of organic crops will alter selection in favour of weed species that are not easy to control either by changes in crop management or by non-herbicidal methods of weed control (Chapter 13). However, integrated crop management will become more important in many areas of crop production, switching the emphasis to favour those weeds adapted to such integrated methods.

Increasing concern about the impact of farming on rural diversity is prompting serious questions about the definition of a weed. Even if a weed in a crop is causing a reduction in crop yield it may be considered that, at a national level, its beneficial effects on populations of insects that are the food for birds outweighs this negative effect. As a consequence farmers may be asked to manage fields on a conservation basis, eliminating only the noxious weeds and not controlling those species that have other environmental benefits. Thus weed control may be targeted at blackgrass (*Alopecurus myosuroides*) and cleavers (*Galium aparine*) but other weeds such as those in the Polygonaceae (redshank, knotgrass) or chickweed (*Stellaria media*) will be left to provide food for beneficial invertebrates and vertebrates. This approach will provide a severe challenge for farmers and growers in managing crops. It is not changing the impact that weeds have on crops but it is challenging perceptions of the main reason for controlling them, by changing the value placed on the non-crop species.

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Chapter 2
Weed Competition

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Introduction

Weeds compete with crops for environmental resources available in limited supply, i.e. nutrients, water and light. Competition has been defined as 'the tendency of neighbouring plants to utilise the same quantum of light, ion of mineral nutrient, molecule of water, or volume of space'. As a consequence, weeds may reduce yield significantly and impair crop quality, resulting in financial loss to the grower or farmer. Thus it has been estimated that on a global basis weeds are considered responsible for c.10% reduction of crop yield, with losses in the tropics possibly exceeding 15%. Global losses in yields of temperate cereals as a result of competition with *Avena* spp. (wild oats) have been estimated as 2.7 million tonnes (Froud-Williams, 1999).

Interactions between crop and weeds may be considered as either direct or indirect, necessitating the adoption of the term 'interference'. Thus, competition between crop and weeds when demands for resources in limited supply exceed those available may be considered as indirect interference, whereas the suppression of growth of one individual by another may be considered as direct interference. The latter results from the release of phytotoxic chemicals by one species to the detriment of the other, a process referred to as 'allelopathy'. Evidence for allelopathy is relatively scant in temperate agricultural systems and for this reason will not be considered here in detail.

In some instances, yield reductions may exceed 50% or even lead to complete loss of marketable yield, e.g. in lettuce as a result of leaf chlorosis and excessive internode elongation. For horticultural crops such as carrots, grown to specific market requirements, reduction in root diameter may lead to crop rejection.

Not only are losses evident in edible crops. In ornamentals and woody species, plants subject to competition may appear etiolated and unattractive or unsuitable for commercial use. In perennial crops such as fruit trees, effects of competition during the year of establishment may be evident throughout the life of the crop, despite subsequent weed removal. Thus failure to control weeds during the first year of bush and cane fruit may depress extension growth by as much as 60%.

In grassland, the presence of indigenous grasses and broad-leaved weeds among sown species may not reduce the overall total biomass, but may impair palatability and digestibility to the grazing ruminant. However, presence of some broad-leaved herbs, e.g. plantains (*Plantago* spp.), which contain trace elements may be considered desirable, particularly in organic systems, whereas others such as *Rumex obtusifolius* (broad-leaved dock) may reduce grass yield by as much as 20% from 25% ground-cover. Whilst the presence of native grasses, e.g. *Festuca rubra* (red fescue), may extend the grazing season, other species such as *Poa annua* (annual meadow-grass) may depress yields while offering little productivity.

Weeds may also indirectly compete with crops and hence reduce yield by competing for pollinators; for example, this may be evident in plum and apple orchards from the presence of *Taraxacum officinale* (dandelion), which competes for pollination by honeybees. In addition, the presence of weeds whose life cycles are not in phase with the crop, e.g. *Elytrigia repens* (couch grass) in small-grain cereals, may lead to delays in harvest and incur additional costs of grain drying. Conversely, for those species with reproductive cycles in phase with the crop, grain contamination may incur additional economic penalties.

In addition to direct interference with crops through competition, weeds also interfere directly as plant parasitic species such as *Cuscuta*, *Orobanche* and *Striga* growing on crop hosts or through the release of toxic substances (allelochemicals) as reported for *Cyperus rotundus* (purple nut-sedge). Parasitic weeds may deprive their hosts of water and or nutrients as a result of root and shoot attachment, as well as possibly diverting manufactured assimilate from the foliage.

Not only do weeds interfere with crops and other weed species (interspecific competition) but also with one another (intraspecific competition). Hence, studies of competition need to take into consideration not only the density of weeds present, but also the species concerned. So too, the nature of the crop, cultivar, time of sowing and environmental conditions need to be included. Recent evidence would suggest that competition for below-ground resources (water and nutrients) may be at least as important, if not more so, as competition for light, which is not usually limited unless differential canopy heights exist between crop and weed.

In some studies of the relationship between crop yield response and weed control a disappointing picture has emerged, for the cost of weed removal has at times exceeded the benefits of yield response. For example, in some instances involving the removal of low densities of annual broad-leaved weeds from cereals with herbicides, as little as a 2% yield response has been observed. Hence, it is imperative to identify the most competitive species and the density at which economic yield loss occurs. It is unfortunate that the cost of control of the more intransigent and competitive species is often greater than that of the less competitive ones.

In general, the earlier the emergence of the weed relative to the crop, the more competitive it is likely to be. Initial infestations of weeds usually have little effect on final yield provided that they are removed early, before competition occurs. Similarly, if the crop is maintained weed-free initially, then later-emerging weeds will exert little competitive effect.

Methods of studying competition

Critical period of competition

The critical period of competition is the period during which the crop must be maintained weed-free to avoid irreversible damage through competition, i.e. the period between too late a removal of weeds and too early a relaxation of weed control, which would result in yield loss. Thus in studies of competition two questions are particularly pertinent: firstly, for how long can weeds be allowed to remain before there are irreversible effects on yield, and secondly, for how long must the crop be kept weed-free in order that weeds which subsequently establish do not impair yield?

Experiments designed to investigate the critical period or weed-free maintenance period are especially suited to field evaluation. Essentially, such studies involve the removal of weeds from selected plots at various intervals throughout the life of the crop and conversely allowing or causing the establishment of weeds at similar intervals in other plots (Figure 2.1). Measurement of final crop yields enables the necessary interval during which the crop should be maintained weed-free to be determined.

The identification of the critical period of competition is of particular importance to organic growers in order that mechanical weed control operations are carried out at the optimum time. With conventional systems, knowledge of the critical period allows judicial selection of pre-emergence herbicide applications of

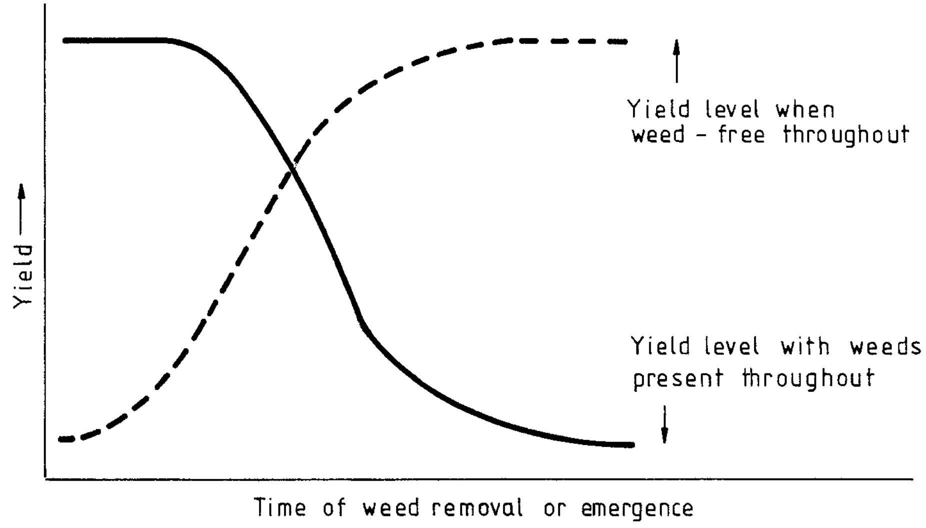

Fig. 2.1 Relationship between final yield and presence of weeds for various durations of crop growth. Solid line: effect of allowing weeds to remain for different periods prior to removal. Broken line: effect of maintaining crop weed-free for different periods prior to relaxation of weed control.

sufficient persistence to prevent weed emergence. Even with conventional systems, the desire to reduce dependence on herbicides renders it essential to identify the period during which the crop should be maintained weed-free. For genetically modified herbicide-resistant crops, potential reductions in herbicide use may result from application of non-persistent post-emergence herbicides during the critical period.

Additive designs

From an agronomic perspective, the effect on crop yield of increasing the density of weeds relative to that of the crop is perhaps the most useful measure of weed competitiveness. Hence, most competitive studies have involved additive designs, in which the density of one species (usually the crop) is maintained constant while that of usually one other (weed) varies, to enable a yield loss/density relationship to be plotted. Typically this involves the use of pot, box or field experiments in which the crop is maintained at recommended agronomic densities whereas the weed density varies from zero to a value often greater than for the crop, with several intermediate densities to enable a curve to be fitted.

Relationships between weed density of a single species and crop yield are potentially useful in that they provide a predictive assessment of yield loss for a specific weed density. The relationship between weed density and yield is generally curvilinear, with the greatest rate of yield reduction at relatively low weed densities and correspondingly less yield reduction per individual weed at higher densities as a consequence of intraspecific competition. Hence, the relationship assumes an asymptote, beyond which no further yield loss is incurred. The precise nature of this relationship is discussed later in this chapter in the context of models of crop–weed competition. The additive design has been criticised in that it does not actually provide information on competitive ability. Furthermore, as density is increased, inevitably spatial arrangement and proximity factors will be affected.

Replacement designs

Another approach often undertaken in glasshouse pot studies, is a replacement design in which the total plant density is maintained constant, but the relative proportion of the species is varied from zero to a pure stand (termed a proportion of 1.00, or 100%). Additionally, for each species, pure stands must be included at each of the densities in the mixture to enable intraspecific competition to be determined. This has been referred to as a replacement or substitutive design and enables an assessment of relative competitive ability. This approach is particularly relevant to studies of intercropping and of differential fitness between herbicide-resistant and -susceptible weed biotypes.

Replacement designs have four possible outcomes as a consequence of the interaction between two species in mixture: no interference; one species outcompetes the other; neither species contributes its potential to total yield in mixture; and each species contributes more total yield in mixture than in pure stand (Figure 2.2). Such designs also enable a measure of aggressivity between species, referred to as the relative crowding coefficient (RCC), which is particularly appropriate where one species out-performs the other.

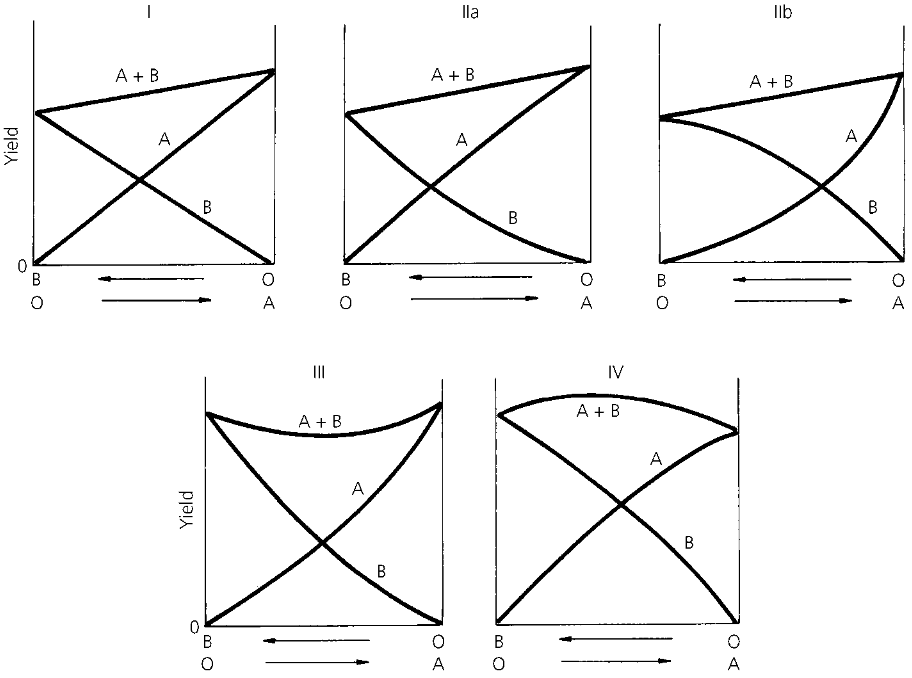

Fig. 2.2 Possible outcomes of replacement design experiments. I: no interference; IIa: species A more competitive; IIb: species B more competitive; III: mutual antagonism; IV: symbiosis. (*After Radosevich, 1987.*)

Alternatively, calculation of relative yield total (RYT) is more appropriate where the total yield in mixture cannot be predicted from pure stands. RYT values of 1.0 indicate species are competing fully for resources and values less than 1.0 imply that each species is prevented from achieving full resource use (sometimes used as evidence of allelopathy), whereas values greater than 1.0 indicate that species show full resource use complementarity, i.e. make different demands appropriate to intercropping.

A criticism of replacement designs is that they do not represent the situation in the field, where the crop is normally maintained at constant density.

Compartmentalisation of resources

A means of differentiating between competition for above-ground resources (light) and below-ground resources (water and nutrients) is the use of the divided box technique. This involves the use of partitions to compartmentalise foliar and root systems of competing species to produce four possible combinations: no competition; shoot competition only; root competition only; or full competition (Figure 2.3). Such an approach provides a particularly useful means of identifying the physiological basis of competition, but has been criticised because of the restricted soil volumes often employed and the possibility of greater resource availability to those treatments involving no competition. Nonetheless, it does enable resources such as water and nutrient limitations to be quantified.

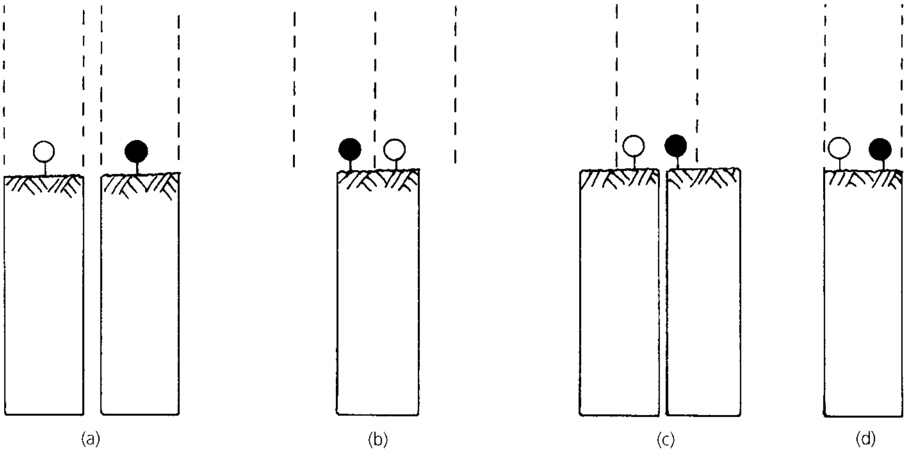

Fig. 2.3 Divided box technique. a) no competition; b) root competition only; c) shoot competition only; and d) full competition.

For example, the time of emergence of wild oat (*Avena fatua*) relative to spring wheat was investigated using boxes that allowed separation of root and shoot competition. The RYT for mixtures of wild oat and wheat under different forms of competition and different sowing times was close to unity, indicating that the two species competed fully for limiting resources. Wild oat was more competitive than wheat when the two species were sown simultaneously, largely because of its greater root competitive ability, the shoot competitive ability being similar. When wild oat was sown three weeks later than wheat, wheat was more competitive than wild oat and panicle production was prevented. Thus it was concluded that to prevent wild oat from returning seed for further re-infestation, it was necessary to control emerging seedlings within the first three weeks of drilling the crop. However, if nitrogen and water are available in non-limiting amounts, light interception may become the limiting resource. In one study *Avena fatua* reduced leaf area of the crop at early growth stages, but reduced light penetration at later growth stages.

Models of yield loss relationships

Previously investigations of crop–weed interactions have indicated a sigmoidal relationship between yield loss and increasing weed density. Such studies have indicated that below a given weed density, yield loss is not apparent, the so-called absolute threshold. This is because, at low weed densities, yield loss significantly different from that in the absence of weeds may not be demonstrable. For a true sigmoidal relationship, yield loss would approach zero as weed density decreases, but would not actually equal zero until weeds were absent. This observation has resulted in the realisation that the relationship between yield loss and weed density conforms to a rectangular hyperbola. The hyperbolic model has two parameters which may be used as indices of competition, asymptotic yield loss (A) and yield loss per unit weed density (I). Yield loss per individual weed decreases as plant density increases and yield approaches an asymptote at high weed densities due to intense intraspecific competition (Figure 2.4).

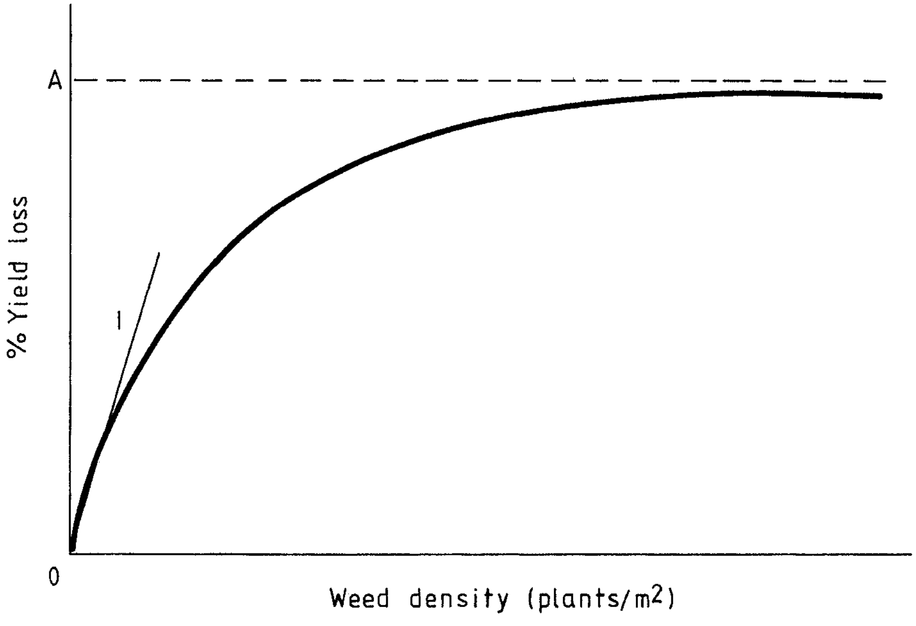

Fig. 2.4 Relationship between yield loss and weed density. I = yield loss per weed plant at low weed density; A = maximum yield loss. (*After Cousens, 1985.*)

Thresholds

The lowest density at which it is possible to demonstrate yield loss is referred to as the biological or statistical threshold; but its determination is subject to experimental design rather than biological concepts. Nonetheless, attempts have been made to define thresholds, at densities above which financial returns would accrue in response to weed removal. The simplest and most easily calculated threshold is the economic threshold, based on decisions made in any single year. It may be defined as 'the weed density at which the cost of herbicide and its application would just equal the financial benefits from weed control in that year'. Its determination will be influenced by choice of herbicide and commodity price of the crop concerned. Such a threshold takes no account of future infestation of subsequent crops and, although relatively easy to calculate, is of limited value. Thresholds designed to realise financial benefits over a number of years are referred to as 'economic optimum thresholds'. Models enabling the determination of economic optimum thresholds have been constructed for the annual grass-weeds *Alopecurus myosuroides* (blackgrass) and *Avena fatua* (common wild oat) in winter wheat. For example, an economic optimum threshold of 2–3 seedlings/m^2 was calculated based on the use of the herbicide difenzoquat for wild oats and 7.5 seedlings/m^2 for blackgrass, based on early post-emergence application of chlorotoluron. In both instances these values are considerably lower than their respective single-year economic thresholds of 8–12 and 30–50 plants/m^2. Furthermore, even at densities of only 1 plant/m^2, wild oats may exact a yield penalty in spring barley of 1%.

These values are comparable to estimated thresholds reported for *Avena sterilis* ssp. *ludoviciana* (winter wild oat); *Lolium multiflorum* (Italian ryegrass) and *Bromus sterilis* (barren brome) of 7–12, 25–35 and <40 plants/m^2 respectively in wheat in north central Italy. The comparable value for the broad-leaved weed *Galium aparine* (cleavers) was 2 plants/m^2 although, in the absence of nitrogen, thresholds of both brome and cleavers were negligible. Fixed guide values for economic thresholds have been adopted in some countries, notably Germany, where their use has been considered to be more profitable than prophylactic herbicide application. Fixed guide values for grass-weeds, excluding *Avena fatua*, were 20–30 plants/m^2 and for broad-leaved species, excluding *Galium aparine*, 40–50 plants/m^2.

Limitations to the adoption of thresholds

Obviously, no single threshold can be applied to all cases, for determination of thresholds depends on the choice of herbicide, each of differing cost and efficacy, while thresholds also differ on the basis of potential crop yield and competitive ability. Thresholds tend to be higher as herbicide costs increase; but even if costs were equal, thresholds would be reduced for those products of greatest efficacy.

A practical example of how thresholds may differ in relation to potential crop yield is evident in Australian cereal rotations. Inclusion of atrazine-resistant oilseed rape may only be more economic than conventional rape when grassweed densities exceed those at which yield of the conventional cultivar would be reduced below that of the lower-yielding resistant variety.

Thresholds do not take account of the fact that weeds often occur in mixed infestations and are aggregated rather than distributed uniformly. Furthermore, allowance needs to be made for variation in soil type, which may account for variation in competitive ability between geographic locations, as a consequence of differences in nitrogen status and soil moisture availability. Evidence for considerable variability between seasons in weed competitiveness is apparent from observations in the Netherlands that yields of maize were reduced in competition with *Echinochloa crus-galli* (barnyard grass) at a density of 100 plants/m^2 by 8% in one year, but 82% in the following year. The greater yield reduction in the second year was attributed to delayed crop emergence and greater moisture stress during a dry year.

Threshold populations may exceed levels likely to be acceptable to farmers; in some cases zero thresholds may be needed to prevent re-infestation and implications for sequential cropping. In *E. crus-galli* and *Abutilon theophrasti* (velvetleaf) at densities of 1–5 plants/m^2, seed return may exceed several thousand per plant.

Threshold values are also influenced by agronomic practices such as tillage regime as a consequence of differences in competitive ability and reproductive output of weeds, as well as by biotic factors such as predation and disease incidence. Thus although thresholds based on a single year may have limitations in their application, their adoption offers a means of assessing likely weed impact on yields. In Germany, the use of single fixed guide values for economic thresholds has been found to be more profitable than prophylactic herbicide application.

Empirical versus mechanistic models

A number of empirical models have been developed to describe the relationship between weed density and crop yield. However, attempts to describe economic thresholds based on weed seedling densities as decision aids in weed management have proved problematic for various reasons, including aggregated distribution, unevenly aged cohorts of emergence, and spatial and temporal variation. To take account of such factors as relative time of emergence and environmental variation, mechanistic models have been developed that consider the physiological demands of crop and weed. The use of simulation models based on observed data sets has indicated good correlations for several crop–weed interactions, including tomatoes and *Solanum* spp. However, the simulated model over-estimated competition with a transplanted crop relative to that of a direct-seeded one as a result of the differential between crop and weed emergence. Nonetheless, it was concluded that empirical models have a role in weed management decisions at the agronomic level, whereas the mechanistic approach was considered particularly suited to research purposes designed to investigate mechanisms of competition.

However, whereas empirical models based on weed density were not a particularly useful predictor of yield loss, models based on relative leaf area were of greater value.

Relative ground-cover and weed biomass

A major constraint to the implementation of thresholds based on weed densities is the fact that weed seed germination is often protracted. This results in several cohorts of seedling emergence with individual cohorts differing in their intrinsic competitive abilities. This has prompted the search for an alternative means of predicting potential yield loss based on factors other than plant density, including relative ground-cover, based on leaf area. Thus, for example, alternative fixed guide thresholds for broad-leaved weeds in cereals based on percentage ground-cover are 5–10%. Such an approach allows for the effects of different relative times of emergence and mixed weed infestations to be predicted. The relative leaf area model relates yield loss to relative leaf area of weeds shortly after crop emergence using relative damage coefficients, previously determined, and is derived from the hyperbolic yield–density relationship, thus accounting for weed density.

Alternative approaches to the prediction of yield loss in response to multi-species weed infestations include multiple regression equations designed to describe the relationship between yield loss and above-ground weed biomass. Such multiple species associations may over-estimate yield reductions as they need to take account of inter- and intra-specific competition.

Crop equivalents

Herbicides form a large proportion of total variable costs in crop production and, as economic margins are reduced, greater awareness of weed competitive ability is required to justify the cost of weed control. Whereas yield responses to the removal of grass-weeds tend to be readily demonstrable, responses to the removal of broad-leaved species are not always evident. Yield responses to the removal of broad-leaved species appear to be influenced more by the species present than by density (Figure 2.5). Broad-leaved weeds tend to occur in mixed assemblages, each of differing competitive ability, thus precluding a direct relationship between yield response and removal of individual species. That weeds differ in their competitive abilities necessitates a competitive index. The relative life cycle of individual species is likely to be indicative of the duration of competitiveness. For example, in a winter cereal or rape crop, winter annual weeds which senesce early relative to the crop are likely to offer less competition than those that are entirely in phase with the crop. If it is assumed that competition results in direct replacement of crop biomass by weed biomass, then a system of crop equivalents may be constructed. Here, the competitiveness of each individual of a particular weed species may be determined on the basis of the displacement by it of an

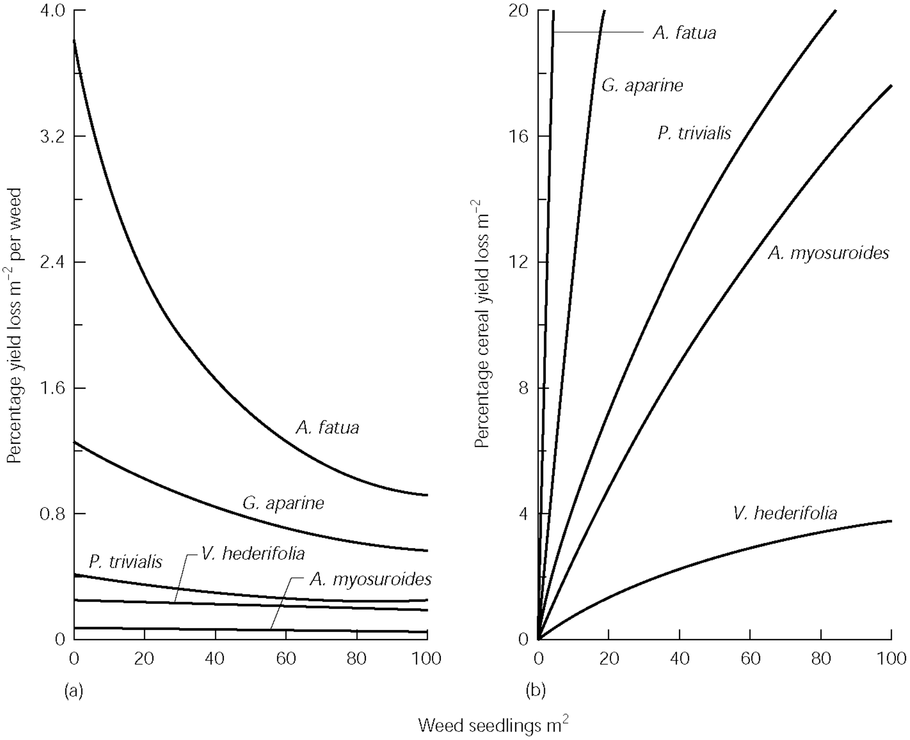

Fig. 2.5 Effect of weed density on (a) yield loss/m^2 per weed and (b) yield loss/m^2. (*After Wilson & Wright, 1990.*)

equivalent amount of crop biomass. This would enable competition from mixed infestations to be integrated with yield loss, and thresholds could be applied.

Crop equivalents (CE) are derived from the assumption that all competition is by direct replacement. It is considered that broad-leaved weeds totalling 10 CE/m^2 should be regarded as the economic threshold, but allowing for a margin of safety this could be reduced to 5 CE/m^2. Thus weeds totalling 5 CE/m^2 in a crop of winter wheat (at a population of 245 plants/m^2) would give a predicted yield loss of YL 2%, calculated according to Equation 2.1.

$$\mathrm{YL} = \left(\frac{\mathrm{CE}}{\text{crop density} + \mathrm{CE}}\right) \times 100 \tag{2.1}$$

Good correlations of predicted versus observed crop equivalent values have been observed. However, for those species that senesce early during the life of the crop the number of individuals that could be tolerated without unacceptable yield loss was greater than predicted, whereas for those that are in phase with the crop, fewer could be tolerated than predicted.

While it is evident that weed biomass may directly replace crop biomass at low weed densities, this is not so as weed density increases, nor for those species with life cycles in phase with the crop. Thus, for *Avena* spp. and *Galium aparine*, competition resulted in additional biomass, possibly accounting for the underestimates of crop equivalence based on prediction through replacement. Thus, in the example given above, assuming an economic yield response of 2% loss, it would have been uneconomic to control *Avena fatua* at densities less than 0.5 plants/m^2, *Galium aparine* at less than 1.6 plants/m^2, *Alopecurus myosuroides* at less than 8.3 plants/m^2 and *Veronica hederifolia* (ivy-leaved speedwell) at less than 39 plants/m^2.

That competitive ability is related to both weed life cycle relative to that of the crop and to geographic location is evident for comparable studies in spring barley in Northern Ireland, where crop equivalents for *Matricaria perforata* (scentless mayweed), *Galium aparine* (cleavers), *Stellaria media* (chickweed), *Polygonum lapathifolium* (pale persicaria) and *Chrysanthemum segetum* (corn marigold) were 0.02, 0.19, 0.41, 0.75 and 0.85 respectively.

Selected case histories

Vegetable crops

Onions

The onion crop is particularly vulnerable to weed competition as it presents very little canopy and is slow to establish. Studies conducted at the former National Vegetable Research Station, now Horticulture Research International, indicate that for bulb onions, provided that weeds were not allowed to remain for longer than five weeks after 50% crop emergence, there were no adverse effects on yield. However, if weeds remained beyond five weeks, then there was a yield loss of 4% for each day that weeds were allowed to remain over the following two weeks. There was little correlation between weed density and final crop yield over the range 150–850 weed plants/m^2, albeit at lower densities the onset of competition was delayed. It was found necessary to prevent weed establishment for approximately seven weeks after 50% crop emergence, to prevent yield loss. Thus in onions there exists a critical period of competition during which the crop must be maintained weed-free to avoid yield loss. By the time that the crop had entered the exponential phase of growth, weed weight per unit area was 20 times that of an unweeded crop, with almost half of the applied nitrogen taken up by the weeds.

A similar situation is apparent for salad onions, failure to control weeds resulting in yield reductions of up to 96%. However, a single weeding timed correctly in one study could avoid yield loss, although the timing varied from 21 to 56 days after 50% crop emergence. In other investigations neither single nor multiple weedings within the optimum period consistently prevented yield reductions.

Beans

In broad beans, the earliest date that weed control may be relaxed to avoid yield loss appears to precede the date at which weed control must commence to prevent yield loss. Thus weeds can be tolerated for much of the growing period before removal, or the crop only needs to remain weed-free for a short duration. Comparable studies with field beans have indicated that whereas for an autumn-sown crop there may be a critical period, for spring-sown cultivars this may be relatively short or totally absent, although failure to remove weeds could exact yield losses of 46–48%. The duration of the critical period is dependent on the yield reduction acceptable. Thus in experiments conducted with runner beans, the critical period was less than 25 days if 5% yield loss was considered acceptable, and non-existent at the 10% level.

Miscellaneous vegetable crops

In a large range of horticultural vegetable crops no specific critical period is evident, so that a single weeding timed correctly should, in theory, avoid yield loss. For several crops grown during the summer period, weed removal on a single occasion four weeks after 50% crop emergence results in yields no different from that of weed removal throughout the life of the crop. Examples are provided by carrots, red beet, drilled summer lettuce, drilled summer cabbage and cucurbits. The duration of the critical period is also lessened if crops are established from modular transplants, as is the case for most horticultural brassicae and leeks. However, while the presence of weeds in transplanted spring cabbage throughout the autumn and winter had no effect on yield provided they were removed prior to the spring, failure to remove them resulted in small, marketable heads and extended internodes. In particular, *Stellaria media* was most competitive, increasing between two- and four-fold in response to nitrogen application.

Tomatoes

Reductions in yields of processing tomatoes caused by infestation with *Solanum* spp. (nightshades) conducted in Ontario, Canada, indicated that losses were greater for seeded than transplanted crops. In particular, stomatal conductance and transpiration rates of seeded tomatoes decreased more rapidly with increased nightshade density than did those of transplanted crops. Yield loss plotted against weed density provided an excellent fit to the hyperbolic model. However, yield was reduced to a lesser extent when the seeded crop was sown at high density in double rows. Whereas the minimal critical period of a direct-seeded crop varied from seven to nine weeks after sowing, for a transplanted crop it was four to five weeks. Competition in seeded crops could be attributed both to reductions in light interception due to shading and to moisture stress resulting in stomatal closure. In contrast, competition between weeds and transplanted tomatoes appeared to result primarily from shading rather than water stress, for although stomatal conductance was lower in the presence of weeds, xylem pressure potential and canopy temperature were unaffected. Because of the extreme sensitivity of tomatoes to herbicides, mechanical weed control was necessitated, but whereas transplanted crops only required a single weeding, direct-seeded crops required a minimum of two weed control operations. Comparisons of competition between tomatoes and *Solanum nigrum* and *Solanum ptycanthum* indicate that *S. ptycanthum* is the most competitive, reducing interception of photosynthetically active radiation as a consequence of its greater height and leaf area (Fig. 2.6). Elsewhere, the effects of *Echinochloa crus-galli* on tomato yields indicated that at the vegetative stage of growth shoot weight was unaffected, but as growth progressed dry weight was decreased at weed densities over the range 16–64 per metre length of row. Marketable yield was reduced by 26% at 16 plants/m and 84% at 64/m. Comparable reductions in yield at these same densities in competition with *Chenopodium album* were 17 and 36%. Reduction in growth at the flowering and early-fruit stage may be attributed to competition for nitrogen and potassium.

Spatial arrangement of weeds relative to crop can greatly affect potential yield reduction. For example, increasing aggregation of *Echinochloa crus-galli* resulted in increased intraspecific competition, but reduced interspecific competition. Thus yields of direct-seeded tomatoes were reduced to 20–75% of the weed-free yield when the weeds were randomly or uniformly distributed, but to between 10 and 50% of weed-free plots when the weed distribution was clumped. Thus the single-year economic thresholds for barnyard grass per metre of crop row were 25, 19 and 15 for uniform, random and aggregated distributions respectively.

Root crops

Swede and sugarbeet

In contrast to several of the horticultural vegetable crops considered previously, swede and sugar beet are present in the ground for a longer period, and because establishment is under cool conditions early development of the leaf canopy is slow. Yield losses are greatest following competition with tall growing weeds such as *Sinapis arvensis* (charlock) in the case of swede and *Chenopodium album* (fat hen) in the case of sugar beet. The latter may reduce yield by as much as 95% as a consequence of shading and competition for light.

For sugar beet, the critical period is determined by sowing date, weed species composition and rainfall during crop establishment. When rainfall is frequent, the critical period can shorten from four weeks for a March sowing to two weeks for a sowing in early May. However, if rainfall is slight during this period there may not be a critical period. Thus, competitive relationships are not uniform across environmental gradients. In theory, a single weeding timed between four and six weeks after emergence could prevent yield loss, but failure to remove weeds during the next six weeks may result in 1.5% yield loss for each day that they remain. In practice, weed control in sugar beet requires repeat dose

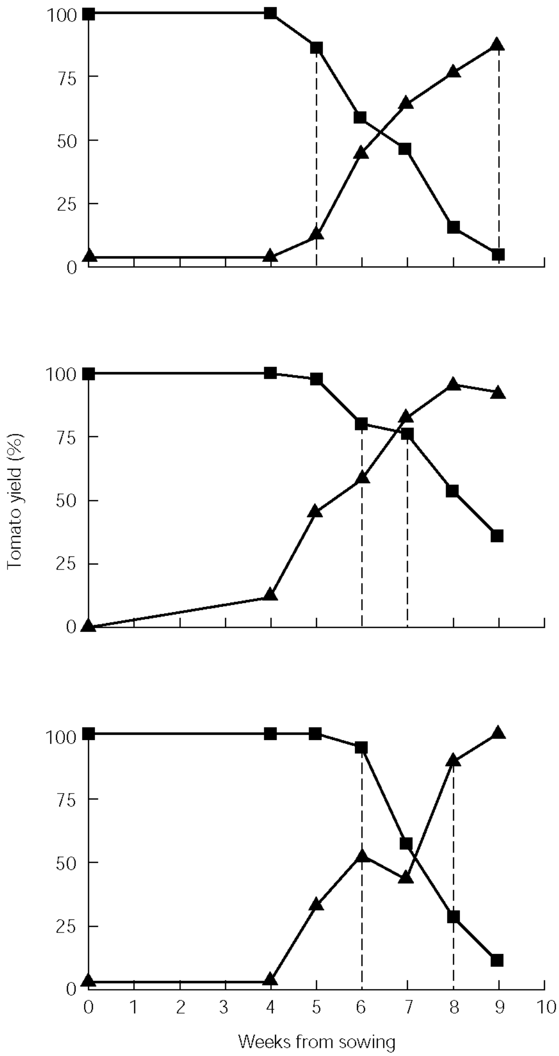

Fig. 2.6 Tomato yields expressed as a percentage of weed-free control plots kept weed-free (triangles) or weed-infested (squares) for various intervals in three consecutive years. Dashed lines indicate durations of the critical period. (*After Weaver & Tan, 1987.*)

applications of reduced-dose herbicides to address the sequential flushes of weed seedlings characteristic of peat soils. As with weeds in cereal crops, species differ in their relative competitive abilities, such that reported reductions in sugar yield following competition with *Polygonum aviculare* (knotgrass), *Matricaria perforata* and *Chenopodium album* were 23, 28 and 42% respectively. *Chenopodium album* is also responsive to nitrogen, resulting in luxury consumption and increased shading ability. At final harvest root/shoot ratios of 2.22 have been reported in the absence of weeds as compared with 2.00 in the presence of weeds, indicative of shading.

Selection of sugar beet cultivars of upright growth habit could alleviate effects of competition for light experienced by more prostrate cultivars. Furthermore, the possible adoption of herbicide-resistant beet could enable restriction of non-selective but non-persistent herbicides to the duration of the critical period. Later-emerging seedling cohorts may have negligible effects on yield, but may provide a valuable energy source to farmland birds, although replenishment of the soil seed bank may have implications for sequential cropping.

A similar situation has been demonstrated for swede, such that one weed removal, six weeks after sowing, resulted in a yield similar to that of a crop maintained weed-free throughout. Delaying weed control until 12 weeks after sowing resulted in a yield reduction comparable to no weed control. Further experiments indicated that light was not the limiting factor. Weed competition up to 12 weeks after sowing reduced the number of secondary cambia of the hypocotyl, but this was not sufficient to account for the reduction in storage organ capacity, for it was the ability to increase leaf area index that was severely restricted.

Arable crops

Oilseed rape

There is little evidence of yield reduction from broad-leaved weeds in oilseed rape, although the necessity to control *Galium aparine* is evident, given that it competes with the crop, interferes with harvesting and contaminates the seed. However, grass-weeds and volunteer cereals, in particular at densities in excess of 70 plants/m^2, may reduce crop growth, although rarely is the effect carried through to yield as oilseed rape has a tremendous capacity to compensate. Furthermore, there is little evidence that early weed removal is essential for maximum yield. Rather, herbicide efficacy appears to be of greater importance than time of removal, in contrast to weeds in cereals. Despite growth reductions of 25–40% and 65–81% at volunteer barley densities of 200 plants/m^2 and of 50–91% at densities of 400 plants/m^2, good recovery was observed, especially for early-sown crops. Thus yields were reduced by 16–39% at a volunteer barley density of 200 plants/m^2 and by 78% at 400 plants/m^2. Although herbicide application reduced yield losses to 5%, cost of treatment could exceed financial returns: if a yield reduction of 8% is considered, with an approximate estimate of economic thresholds based on average yields of 2.8 t/ha, a crop value of £295/t and 1.7 treatments per hectare, then financial benefits could be obtained from weed control in late-sown crops (mid-September) at barley densities of 100–200 plants/m^2. For early-sown (mid-August) crops, volunteer barley at densities as great as 285 plants/m^2 may not impair yield, but may act as a green bridge for transmission of cereal foliar pathogens.

Relative weed biomass has been considered to be a better predictor of potential yield loss in oilseed rape than has weed density. A 5% yield loss has been predicted from densities ranging from 1.4 to 328 plants/m^2 as compared to a narrower range of 1.4–10.6% relative weed dry weight. Variation between years and sites is usually attributed to weather. A major difficulty in predicting yield loss for oilseed rape is the interval between assessment date and harvest, although crop dry weight in December provided a useful predictor of crop competitiveness. Plant species differ in the base temperatures necessary for dry weight accumulation and observations indicate that the base temperature required for growth of oilseed rape is greater than that necessary for growth of *Stellaria media* and volunteer cereals. Thus relative values for oilseed rape, barley and *S. media* are +5, 0 and −2°C, indicating that *S. media* will accumulate dry matter at temperatures at which growth of oilseed rape is static.

Spring barley

Investigations of weed competition in spring barley have focused on *Avena fatua* as the major weed problem, but have failed to detect a correlation between yield loss and weed density. This lack of correlation has been attributed to variation in time of weed-seedling emergence relative to that of the crop. Thus, not only are the earliest-emerging cohorts most competitive, but they also contribute the greatest seed return. In Canada, a significant relationship was demonstrated between yield loss of spring barley and relative time of weed emergence. For a given density, percentage yield loss is increased the earlier that wild oats emerge relative to the crop, and gradually diminishes as emergence is delayed. Yield losses derived from regression analysis indicated that for every day that wild oats emerged before the crop, yield loss was 3% over a six-day period. Similarly, yield loss decreased by a similar amount for each day that weed emergence occurred after that of the crop. In the UK, a summary of 51 experiments involving wild oat densities ranging from 8 to 662 plants/m^2 indicated that yield reduction varied from 0 to 72%. In 11 of the experiments, grain loss exceeded 1.2 t/ha, largely as a consequence of fewer ear-bearing tillers. Wild oats increased the fraction of small grains (2 mm) from 13 to 20%, equivalent to a grain loss of 0.58–0.71 t/ha. Although yield loss failed to correlate with weed density, it did correlate with weed dry matter present at harvest. Likewise, in Canada increasing densities of wild oat reduced spring barley yield as a result of interference with tillering, but also reduced thousand-grain weight. Estimated economic thresholds assuming a crop density of 250 plants/m^2, a weed-free yield of 4 t/ha, a grain price of \$100/t and weed control costs of \$30/ha were 45 plants/m^2. Shading by the wild oat canopy reduced assimilation and dry matter partition during grain filling.

Winter wheat

As with spring barley, relative time of weed emergence and density are important determinants of yield loss in winter wheat caused by cohorts of *Bromus tectorum* (downy brome). Yield loss is greatest when emergence is synchronous with the crop. However, considerable variation in yield loss between years could be attributed to differences in moisture availability. Time of weed removal appears to be of greater importance than the level of weed control achieved. Simulation models of competition between broad-leaved weeds and winter wheat conducted in the Netherlands indicate that spring-emerging weeds have negligible effects on yield whereas autumn-emerging cohorts could exact yield losses as great as 20%. The few studies which have considered the critical period of competition in wheat suggest that the onset of competition is a function of not only the species present, but also the weed density. It was found necessary to maintain an organic wheat crop weed-free from sowing until mid-May to avoid yield loss. However, if an acceptable level of yield loss can be ascribed, e.g. 5%, then the critical period was found to begin 506 degree days after sowing (early November) and to end 1023 degree days after sowing (mid-February) (Figure 2.7). The greater the yield loss acceptable to the farmer relative to the cost of control, the shorter was the critical period.

However, the use of the critical period as a management tool needs to take account of the method of weed control being employed. This is because herbicides are often of greater efficacy against relatively young weeds, but they may

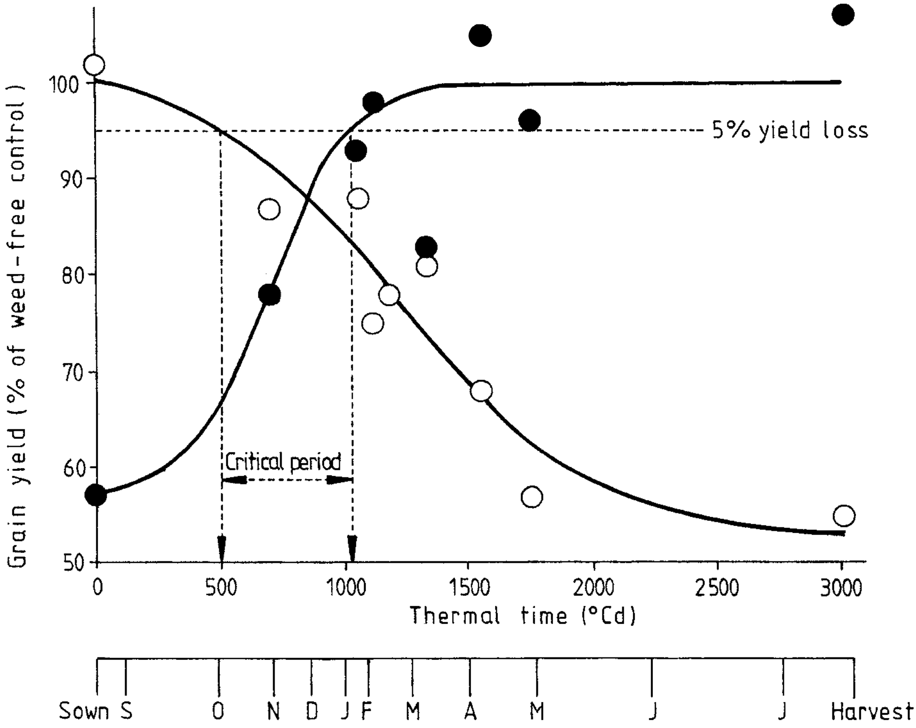

Fig. 2.7 Observed and fitted wheat yield as affected by duration of weed-infested period (open symbols) and weed-free period (closed symbols). (*After Welsh* et al., *1999*.)

not kill larger weeds and they may be adversely affected by weather conditions. Hence, autumn weed removal may be necessary to take account of these factors. Equally, in organic systems, mechanical weeding may be more effective in the autumn when weeds are more susceptible to damage. Yield benefit from weed removal appeared to result primarily from an increase in ear number and to a lesser extent from more grains per ear, whereas thousand-grain weight was unaffected. In Greece *Phalaris minor* (canary grass) at a density of 76 plants/m^2 did not affect yield whereas at densities of 150 and 300 plants/m^2 yield was reduced by 23 and 26% respectively if the weeds were allowed to remain until harvest. No yield penalty occurred at 150 plants/m^2 if they were removed by early April. Black grass densities of 500/m^2 had negligible effects on crop growth before April, but the impact increased rapidly between April and June, resulting in 45% yield reduction if weeds were not controlled.

Evidence that root competition is more severe than shoot competition implies that below-ground resources may be in limited supply. Thus, root competition between *Lolium multiflorum* and wheat was more severe than shoot competition, possibly as a consequence of competition for nitrogen. Partial alleviation of the effects of root competition between black grass and wheat following nitrogen application further points to resource limitation of nitrogen. Further evidence that competition between wheat and *Veronica hederifolia* is primarily for nitrogen is apparent from the fact that crop nitrogen content was reduced in competition with *V. hederifolia*, but that delay in the application of nitrogen until the onset of weed senescence alleviated this effect.

Perennial crops

Fruit and ornamentals

Fruit crops such as soft, bush, cane and top fruit are particularly vulnerable to weed competition during establishment, but may suffer from differences in resource limitation. Thus whereas soft fruit such as strawberries may be most vulnerable to insufficient light availability through shading, top fruit such as apples and pears may be impaired due to limitation of water availability since application of additonal fertiliser fails to alleviate the symptoms. This may be further aggravated by the existence of grass alleys between crop rows, designed to aid accessibility for harvest, and thereby achieve improvements in fruit quality and storage. Failure to control weeds during the year of establishment may incur penalties of growth retardation, not only in the year of establishment but in subsequent seasons also. In Scotland, bush and cane fruit such as raspberries may suffer as much as 60% reduction in cane growth and a loss of almost 80% of planting material as a consequence of shading. Weeds present until late May or early June, although not reducing cane numbers, reduced extension growth, whereas delaying weeding for a further four or eight weeks resulted in 28 and 77% reduction respectively.

Similarly, ornamental bulb crops of narcissus may suffer premature senescence in the first growing season due to the presence of uncontrolled weeds, with subsequent reductions in flower production, bulb size and bulb yield in the second season even if weeds are controlled. Whereas weeds had no adverse effect before flowering, between the end of flowering and onset of senescence they adversely affected yield.

Grassland

Perennial ryegrass swards are subject to deterioration in sward composition as a result of invasion by indigenous grasses. The process follows a chronological sequence with invasion initially by *Poa* spp. (meadow-grasses) and sequentially by *Agrostis* spp. (bents), *Holcus lanatus* (yorkshire fog) and *Festuca* spp. (fescues). Thus although *Poa trivialis* (rough meadow grass) may be palatable, it reduces tiller production and hence ryegrass yield. Even if it is present for only two weeks tillering capacity may be reduced by 23%, and 39% if it is uncontrolled for six weeks. If it is present from the outset of crop establishment, an 80% reduction in tillering capacity may occur. However, nine weeks after establishment, the ryegrass yield in mixture was greater than that in monoculture as a consequence of resource use complementarity.

Factors under farmer control

Opportunities to avoid competition between crop and weeds are afforded by various cultural practices such as use of clean seed, use of stale seedbeds, crop rotation, delayed drilling, appropriate timing of fertiliser application and judicial use of herbicides or mechanical weed control. In addition farmers have flexibility with regard to weed suppression through manipulation of seed rate, row width and cultivar selection.

The time at which a crop is planted is probably the main factor determining the composition of the weed flora, for not only do farmers have a choice of season of planting, but also they have considerable latitude within a season, subject to the economics of crop production. Delayed drilling of winter cereals may incur less yield penalty from the presence of black grass by virtue of differential emergence times, enabling mechanical or chemical removal of early cohorts of emergence, whereas delayed drilling of oilseed rape beyond its optimum timing may actually incur greater yield penalty. Conversely, for spring cereals delayed sowing may not alleviate yield reduction, albeit spring barley may be better able to compensate for this than other cereals. In Canada, delayed drilling reduced density of *Galeopsis tetrahit* (hemp nettle) but failed to reduce biomass, and the effects of competition were similar irrespective of drilling date.

The use of different crop cultivars with differing dates of maturity, competitive ability, canopy attributes etc. may be used to advantage in weed suppression. However, whereas cultivars have been developed for resistance to pests and diseases, variety improvement for increased competitiveness is virtually non-existent for temperate crops. The potential for weed control through crop interference may result from indirect competition or the release of allelochemicals. Evidence for the latter is largely restricted to warm-season crops such as rice and soybean, although residues of rye are also considered allelopathic. There is a need to distinguish between weed suppression and tolerance by the crop; the latter is considered undesirable in that it facilitates replenishment of the seedbank.

In comparisons of weed suppressive ability between various cultivars of spring barley, weed biomass relative to the mean has been reduced by 48% by the most suppressive cultivar whereas for the least suppressive cultivar it was 31% greater. Whereas there was a close correlation between grain yield loss and weed dry matter present, there was no correlation between competitiveness and yield potential. Spring barley cultivars differ in their juvenile growth habit associated with the presence of dwarfing genes. Those with the *erectoid* dwarfing gene have an erect vegetative growth habit whereas those possessing the *denso* dwarfing gene are of semi-prostrate habit. These latter cultivars provide early ground-cover and so may be considered more suppressive.

In Australia, genotypes of spring wheat were screened for competitiveness against *Lolium rigidum* (annual ray grass). Wheat yields were reduced up to 80% and were correlated with weed dry matter production. Traditional wheats (released between 1880 and 1950) were generally more competitive than current varieties. Such varieties tended to show early biomass production and large tillering capacity; they were tall with extensive leaf canopies and shading ability. Similarly, in North America, winter wheat cultivars 73–78 cm tall were poor competitors, whereas taller (>83 cm) cultivars were good competitors, with but two exceptions. Likewise, in the UK, semi-dwarf cultivars of winter wheat which contain the *rht* dwarfing genes are considered less competitive than tall cultivars and consequently may require greater inputs of weed control. In addition to straw height, canopy cover has been implicated in weed suppression as a consequence of reduced penetration of photosynthetically active radiation (PAR). Thus differences in competitive ability appear to be related to various attributes, including rate of establishment, vegetative growth habit, tillering capacity, straw height, leaf canopy architecture and interception of PAR. However, whereas these attributes would appear suitable for manipulation by plant breeding, competition for below-ground resources would appear to be of greater importance, such that manipulation of the canopy is only of value provided that nutritional and water requirements are satisfied.

In addition to choice of cultivar, manipulation of spatial arrangement and crop density may greatly influence competitive ability. Typically, reduction of row width has been shown to favour development of crops rather than that of weeds. The effect of increased seed rates may be similar to that of reducing row widths although the latter may be greater. However, lowering of seed rates may actually reduce yield reduction as a consequence of compensation of yield components, e.g. as increased tillering in small-grain cereals.

In addition to manipulation of seed rate and row width, spatial arrangement of the crop may alter the competitive relationship between crop and weeds. For example, assuming radial expansion of the leaf canopy, rectangular arrangement of crop spacing will result in mutual canopy overlap between rows. Although initial canopy overlap alone would be faster along narrow rows, complete canopy closure would occur earlier in equidistant plantings. This earlier crop closure would restrict weed growth and reduce the impact on crop yield. A study in which crop density of *Avena sativa* was maintained constant, but spatial arrangement was varied, indicated that interspecific competition with *Avena fatua* was greater with spacing of increased rectangularity than with more equidistant spacing. Conversely, interspecific competition between *Lolium multiflorum* and winter wheat resulted in greater crop yield loss with more equidistant spatial arrangements than with increased rectangularity. To some extent, increased seed rates may alleviate such effects.

Summary

Neighbouring plants may interfere with one another directly or indirectly. Direct interference (allelopathy) is less apparent in temperate agricultural ecosystems whereas indirect interference (competition) may result when environmental resources are limited in availability. Competition may occur between different species (interspecific competition) and between individuals of the same species (intraspecific competition). Weeds may reduce economic yields as a result of competition. The relationship between weed density and yield loss is curvilinear and conforms to a rectangular hyperbola. As weed density increases, intraspecific competition increases, reducing the competitive ability per individual.

Competition is often most severe for below-ground resources, water and nutrients, but may change during development, resulting in increased competition for above-ground resources (light). Individual weeds differ in their competitive relationships within specific crops. Early-emerging weed cohorts are most competitive, but species differ in their competitiveness, necessitating a system of ranking.

Various approaches to the study of competition are described, including additive and replacement designs. The use of empirical versus mechanistic approaches to competition is discussed in relation to selected crop examples. It is concluded that although weed density provides the conceptual basis of yield loss relationships, in practice it is less useful owing to differential emergence patterns. The role of thresholds is considered and other approaches to prediction of potential yield loss are discussed. Options available to the farmer/grower to minimise the impact of weed competition are outlined. It is concluded that a number of cultural approaches, including crop spatial arrangement and cultivar selection, may be employed to alleviate the effects of competition, without necessary recourse to herbicides.

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Chapter 3
What is the Weed Seed Bank?

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Importance of the seed bank

The term 'seed bank' is used to describe the reservoir of viable seeds or fruits (hereafter referred to as seeds) found in the soil or at its surface. Viable seeds are those which have the capacity to germinate, given appropriate conditions and dormancy status. For perennial species the concept of the seed bank can be extended to include the 'bud bank', the dormant reserve of vegetable organs, such as dormant buds on rhizomes, which have the potential to regenerate and form new individuals. However, this area will not be considered here, since this chapter concerns the soil seed bank itself rather than plant population dynamics as a whole.

The scale of seed bank density varies enormously between sites, fields and plots, and will depend on many factors such as soil type, previous cropping, cultivation, drilling date and, of course, herbicide use. Estimates of seed bank density typically range from below 1000 seeds/m^2 in pastures or intensively managed arable fields, up to 80 000/m^2 in less intensively managed arable or vegetable fields. However, care must be taken when comparing published values of seed bank density because different methods of sampling and assessment can give very different estimates of seed bank populations.

Soil type will initially determine the potential range of species at a site, and this 'community' will be modified in terms of both composition and abundance by the rotation. Further modification will result from other factors such as the method and frequency of cultivation. Generally, seed densities are lower on heavy clay soils than on lighter soil types. This could be a consequence of the rate of processes such as germination, predation and decay being different with different soil types. Alternatively it could simply be related to the biology of the dominant species. Grass weeds such as *Anisantha sterilis* and *Alopecurus myosuroides* are common on heavy soils and, although the latter does form persistent seed banks, seeds are lost from the soil much more rapidly than for many persistent broad-leaved species.

The seed bank represents the potential weed flora of a site and is particularly important in regularly disturbed habitats such as agricultural systems where successful species are those which mimic the life cycle of the crop. The seed bank enables the continual propagation of species. By providing a means of dispersal in both time and in space it allows species to survive periods when the habitat is unfavourable. A better understanding of plant population dynamics is vital in developing weed management systems that do not rely on herbicide inputs. The changing composition of the seed bank is a critical aspect of population dynamics; therefore seed bank studies must be an integral component of weed management. However, although the importance of the seed bank has been recognised for many years, the difficulties involved with accurately assessing the seed bank have meant that adequate studies of the seed bank have, in the past, been infrequent.

Types of seed banks

The seed bank of an individual species may be classified in terms of its persistence, the length of time that seeds survive in the soil. Previously, four classes of seed banks of the temperate weed flora were identified. Type 1 is typical of predominantly autumn germinators with a transient seed bank through the summer and is characteristic of many large-seeded grass weeds. Type 2 seed banks consist of spring germinators, transient only during the winter and often requiring a period of stratification. Species with Type 3 seed banks have seeds that germinate soon after shedding, usually in late summer, with only a small proportion becoming incorporated into the persistent seed bank. Type 4 seed banks have few seeds germinating after dispersal so that most of the seeds enter the persistent seed banks. The latter two types are usually smaller-seeded species with restricted light and temperature requirements for germination. There have been a number of problems with these classifications as they do not take into account the seasonal dynamics and longevity of the species. In addition, whilst Types 3 and 4 represent extremes of a continuum, many species behave in an intermediate fashion or indeed can behave as both types.

Three alternative classifications of seed bank have been proposed: transient (less than one year, e.g. *Lolium perenne*, *Bromus sterilis*), short-term persistent (more than one year but less than five years, e.g. *Galeopsis tetrahit*, *Viola arvensis*) and long-term persistent (more than five years, e.g. *Stellaria media*, *Capsella bursa-pastoris*). This last category represents the seed bank type most likely to contribute to the regeneration of a community following its destruction. However, it is important to realise that the categories above are ‘typical’ but that the behaviour of an individual seed depends on the precise conditions it encounters.

Spatial distribution

Soil seed banks are notoriously heterogeneous in distribution in both horizontal and vertical planes. Seeds are deposited at the soil surface and, despite the presence of seed dispersal mechanisms in many species, the vast majority of seeds are shed very close to the parent plant. The result is a spatially patchy distribution of seeds concentrated at the soil surface (Fig. 3.1). Seeds of *Senecio jacobaea* have a pappus for wind dispersal, yet studies of this species in pastures indicated that only 0.5% of seeds were dispersed beyond the area of the source stand. For lower-growing species or species without specialist mechanisms, dispersal beyond the immediate neighbourhood of the parent plant is limited. In a study of *Anisantha sterilis*, more than 85% of seeds were disseminated within 1 m of the parent plant. In an arable system, seeds which remain on the plant at harvest have the potential to be dispersed further afield by harvesting machinery. However, even in these circumstances most seeds remain within 5 m of the source area.

Some redistribution of seeds occurs through natural processes both horizontally and down through the soil profile. Horizontal redistribution will occur through hydrological events. Animals and also wind can redistribute seeds on both a large and a small scale. Seeds deposited on the soil surface may become incorporated into the soil profile by movement down cracks or burial by soil-dwelling invertebrates. Independent movement is possible for some species whose seeds have structures such as the awns of *Avena fatua* and *Alopecurus myosuroides,* which twist on wetting and drying. These facilitate small-scale movement of seeds, and possibly aid burial by movement into soil cracks.

Although some natural redistribution of seeds occurs, the greatest heterogeneity occurs in undisturbed habitats. In an arable situation, soil cultivations have the greatest impact on seed distribution. Several recent studies using weed seeds and plastic beads as simulated seeds have investigated the horizontal and vertical movement associated with various cultivation systems. The magnitude of modification will depend on the method of cultivation, soil type, position of seeds in the soil profile and seed characteristics of the species present. The type of cultivation is important for distribution in both vertical and horizontal planes. Ploughing buries over 90% of seeds at the soil surface to below 10 cm, whereas only a small proportion are buried by tine cultivation. A recent study at Horticulture Research International, UK, compared the effects of various implements on vertical distribution and horizontal movement of coloured plastic beads placed at different depths in the soil. This study highlighted differences between implements and the impact of initial depth of sowing on seed movement. From the data, the effects of different sequences of cultivations could be modelled. Similarly, the horizontal movement of seeds under different sequences of plough, tine, harrow and drill has been studied in the field, and seeds were found up to 15 m from the source area after a typical sequence of five operations. The harrow moved seeds the greatest distance (1.6 m), and least movement was recorded with the plough (0.36 m) and the drill (0.26 m). The results have implications for patch dynamics within fields and indicate that cultivation systems based on ploughing will limit horizontal seed movement. Most studies of seed movement have used large seeds or plastic beads as simulated seeds. A study of different types of tine implement showed that smaller oilseed rape seeds were found to move further

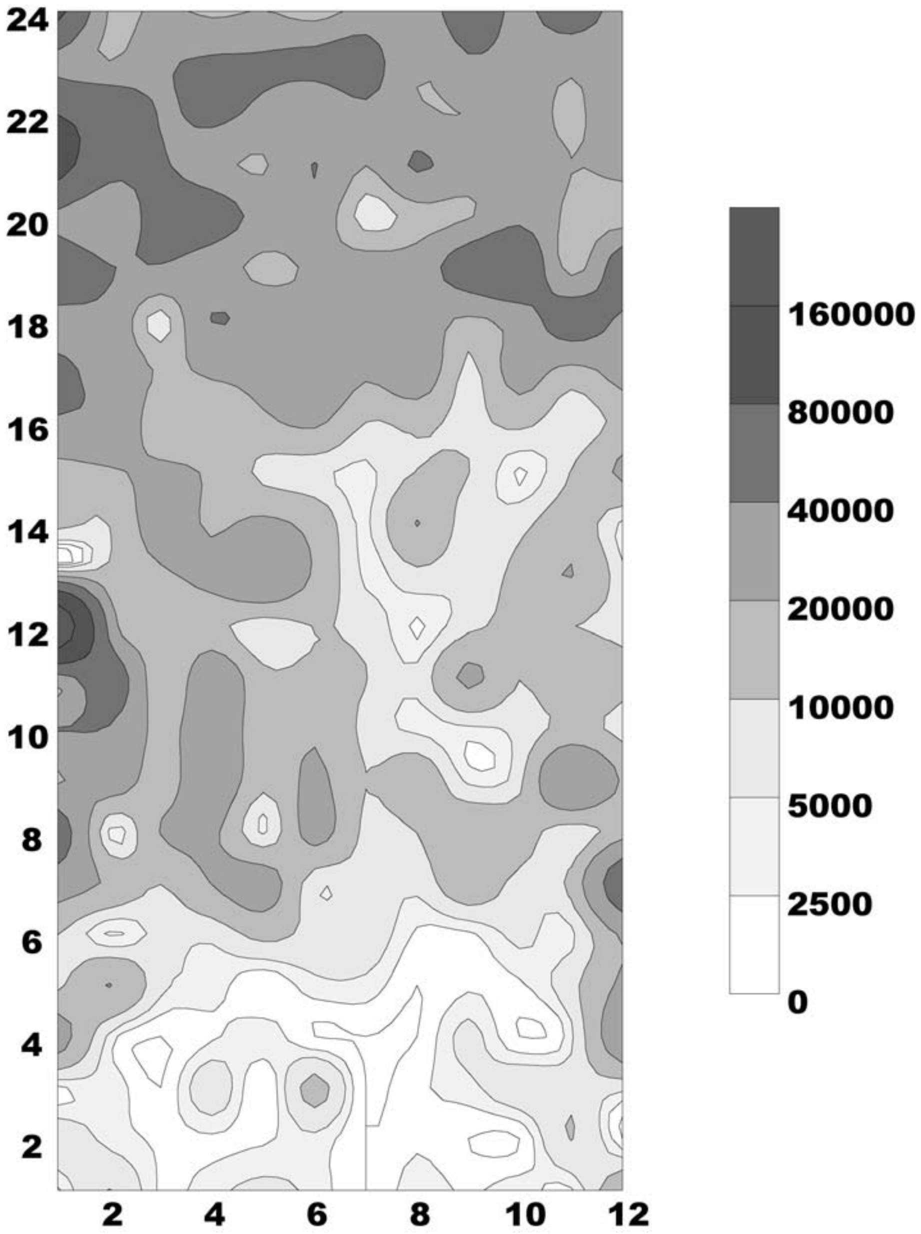

Fig. 3.1 The spatial distribution of *Viola arvensis* in a 12 m × 24 m plot of an arable field with a sandy loam soil.

than larger barley seeds. However, the presence of structures such as awns on large seeds may increase the dispersal distances due to cultivation. Soil type will also affect secondary dispersal. In a study of the vertical movement of several species of grass weeds at Long Ashton, UK, surface-sown seeds were buried more deeply by ploughing on a sandy loam than on a clay soil. Studies of both single and successive passes of cultivations have shown that the effects of each individual pass are not necessarily additive. A single pass of a power harrow followed by a second pass several weeks later may have a different effect on seed distribution from the same two passes of the implement made in quick succession. This is because the first pass of the implement may change the structure of the soil; hence the relative timing and nature of previous cultivations will be an important factor to consider.

Despite the importance of cultivations in the redistribution of seeds within the soil, weeds (particularly grass weeds) remain patchily distributed within fields and these patches remain relatively stable over time. A mapping study of *Alopecurus myosuroides* on several fields indicated that patches remained stable over ten years. This may relate to the relatively short persistence of grasses and therefore less effective redistribution, and to lower absolute seed production. Broad-leaved species are generally more evenly distributed in the seed bank. Although field-scale variability of the seed bank is apparent in terms of weed patches, seed densities vary on many different scales and studies have found highly variable seed bank densities in contiguous samples ranging from 10 cm blocks to 2.5 cm diameter cores.

Sampling strategy

Seed bank densities are usually expressed on an area basis, usually per square metre, but the depth of sampling can significantly affect seed bank estimates. Sample depth will depend on the objectives of the study. If it is necessary to characterise the whole seed bank in a cultivated system, samples should be taken to plough depth. If the objective is to estimate the number of seeds which may germinate and establish, then much shallower sampling may be possible but only if species which germinate from a greater depth are absent. Many studies, particularly of cultivation systems, split cores into different depths to gain an understanding of the differences in vertical distribution. However, this can be difficult on many soils where the substrate is easily compressed.

The inherent variability in the spatial distribution of seeds in the soil means that soil seed bank samples should be made up of many small cores bulked together. However, designing an accurate yet efficient sampling strategy is difficult and there is usually a balance between what is acceptable and what is achievable. Several studies have investigated the number of cores or volume of soil required to estimate the soil seed bank using a variety of statistical techniques, in a range of plot sizes and under different agricultural regimes. Perhaps not surprisingly, the estimates of optimum sampling regime derived from these studies vary greatly. Optimum sampling intensity will depend on both the population mean and the spatial distribution of seeds in the soil. An evenly distributed population at high density is much more easily described than a population at a low density which is patchily distributed. A Canadian study of *Chenopodium album* included a very intensive sampling strategy followed by simulated sampling from this population. It concluded that 60 cores were necessary to estimate seed bank density of this species accurately at the study site. Similar work done at a range of arable sites across England found that within 12 m × 24 m plots, as few as 10 cores, or more than 150 cores, were necessary to describe seed bank populations. Fewest cores were required where populations were evenly distributed, but where many cores contained no seeds of a species, even intensive sampling strategies were inadequate. Usually there will be no knowledge of seed distribution before sampling, and therefore a large number of samples must be taken, whilst accepting that species at low densities may not be accurately estimated by any sampling strategy.

Many of these estimates of optimum sample size relate to the analysis of the total soil sample volume. However, to reduce the total amount of soil to be processed, soil samples are usually mixed and a number of subsamples are analysed. Recent work has shown that increases both in the number of cores in the bulked sample, and in the number of subsamples analysed, improved the accuracy of the estimate of seed bank density. This work concluded that five or six subsamples should be taken from any bulked sample.

The implications of spatial variability for sampling will be significant at different scales, including the sampling pattern across the site and the size of individual sampling units. In the Canadian study of *Chenopodium album*, the relative accuracy of clustered, systematic, random and stratified random sampling was compared for estimation of the seed bank. A clustered sampling regime and in some circumstances systematic sampling did not reflect the seed bank as accurately as other sampling patterns. A random sampling pattern, which includes all areas of the site to be sampled, is therefore usually recommended. If some information about spatial distribution of the seed bank within the area is available, a stratified random sample may be appropriate, e.g. it would be useful to keep samples from the field margin and field centre separate. Different sizes of sampling unit were also compared (1.9–3.3 cm diameter) in the Canadian study, but there were no differences in accuracy of seed assessments in a constant volume of soil. However, in a comparison of corers of 2.5 and 7.5 cm diameter in New Zealand, a larger number of small cores gave a more accurate assessment of the seed bank than a small number of large cores, for a given volume of soil.

The timing of soil sampling is important in view of the dynamic nature of the seed bank. Between-year comparisons must be made by sampling at the same time of year. More detailed studies of plant population dynamics require sampling at several times within a year, which could include the time after harvest when the seed bank is at its highest and a time in the spring after weed germination is complete but before new seed is set.

Assessment methods

A wide variety of methods have been used for seed bank assessment but these can essentially be ascribed to two main categories: germination and extraction.

Assessment of germination, predictably, involves identification of emerged seedlings. In its simplest form soil samples are spread thinly in trays, kept moist and stirred occasionally to encourage germination. Even if the temperature regime is appropriate for the species in question, this technique may not yield consistent assessments of the seed bank between studies, due to differences in periods of germination, frequencies of stirring and routine maintenance of the samples. Dormancy may also be induced in seeds where there is a continuous cycle of wetting and drying. Furthermore, chemicals are sometimes added to break dormancy (gibberellins) or to encourage germination (KNO_3). Germination may also be affected by washing soil through a small mesh to reduce the bulk of material to be analysed. This is because chemicals within the seeds which initiate germination may be 'washed out'. This technique will give an underestimate of the total seed bank because, even where conditions are appropriate for germination and attempts have been made to break dormancy and encourage germination, not all viable seeds will germinate within the period of study. Some seeds will remain dormant and others will die or decay by natural processes before germination is possible. The length of time for which soil samples are maintained varies greatly between studies and the recommended period will depend on the aims of the study and the species in question. If only the readily germinable fraction of the seed bank is important, samples may be maintained for just a few weeks or months, whereas if an estimate of the total seed bank is required, then it is often recommended that samples are monitored for two years, allowing a range of conditions to influence the germination of seeds. However, most seeds tend to emerge in the first year of germination studies, suggesting that an adequate estimate of relative seed density can be achieved in one year. Species which require particular conditions to allow germination must be considered. For example, *Polygonum aviculare* requires a cold treatment and must therefore be maintained through a winter period.

Extraction involves physically picking the seeds out of soil samples and identifying them. A range of systems have been developed, which generally involve either reducing the volume of material to be sorted by washing through sieves or floating off seeds and other organic matter with a dense salt solution, or sometimes a combination of the two. If a sieving technique is used, the choice of mesh size will be crucial in the recovery process and can be manipulated to target particular species. The direct flotation of organic matter from soil can be difficult, particularly on some soil types, and the use of soil dispersants may be beneficial.

However, settling times of up to 12 h are common and flotation has recently been combined with centrifugation to speed up the separation of organic matter from the mineral fraction.

Whichever technique is used for separating the soil sample into fractions, the seeds must then be picked out, identified and counted, and there are several difficulties with such a process. Seed detection can be prone to operator error and is particularly difficult in soils with a high organic matter content, where both extraction techniques leave a considerable amount of material to be sorted. Image analysis has been suggested as a method for automating this process. However, seeds vary widely in their size, shape and angle of viewing, and automated techniques suffer problems in distinguishing seeds from other particles. Human operators have the advantage of the ability to move material around and so view samples from different angles to improve seed detection. As yet image analysis has only been used successfully to count seeds which have already been picked out and sorted by hand.

The determination of seed viability is another problem with extraction techniques. Some studies have tested germinability of extracted seed in incubators or glasshouses, but this has some of the same inherent limitations as direct germination techniques. If soil samples have been stored frozen to prevent seed germination before processing, subsequent analysis of viability through germination will not be possible since freezing is known to reduce the germinability of imbibed seeds. More rapid extraction of seeds using a flotation method is particularly important if extracted seed is subsequently tested for germinability. A commonly used alternative assessment of viability is to squeeze each seed between forceps: those which are resistant to gentle pressure are assumed to be viable. This gives a more rapid assessment of viability, but almost certainly overestimates the viable seed bank.

The identification of species by the physical characteristics of their seeds may also be difficult. Although many seeds can be identified to species, others such as *Papaver* spp. may not be distinguishable from closely related species. A recent study in Israel has overcome this problem for *Orobanche* spp. by using DNA fingerprinting techniques to distinguish between four species of this genus where precise identification is important. Even with direct germination methods, seedling identification at the species level can be difficult and seedlings may need to be grown-on for confirmation.

Comparisons of germination and extraction methods indicate that extraction results in a larger total seed count. Determination of species number is less straightforward and different studies have recorded both fewer and more species using the extraction method. A smaller number of species may be reported where related species cannot be distinguished from each other, but also in some studies because many seeds could not be identified. Essentially, both methods have advantages and disadvantages, and the choice of assessment method must relate to the aims of the study and the facilities available. Germination is appropriate where an assessment of readily germinable seeds is required. It is also a useful technique where seeds of the target species, such as *Calluna vulgaris*, are too small to be identified without high levels of magnification. However, germination techniques do not record seeds which remain dormant, succumb to fungal attack, lose viability or simply do not germinate through the period of study; therefore in these cases seed densities will be an underestimate of the total seed bank. In most agricultural situations in north-west Europe, extraction can recover all important species, although some closely related species will remain unidentified unless techniques such as DNA fingerprinting can be used. Extraction methods give an estimate of the total seed bank rather that the seed bank which is readily germinable, and can also give an immediate assessment where required. However, they are tedious techniques to use which tend to overestimate the seed bank because of the difficulties of directly assessing seed viability, and they can be influenced by the subjectivity of the operator.

In summary, the methodology used to assess the soil seed bank will greatly influence both the qualitative and quantitative estimation of seed banks. Sampling strategy can vary in terms of timing of sampling, size of corer, depth of sample, number of cores, pattern of sampling and subsampling. Along with the obvious, inherent differences between assessment by germination and by extraction, there are also varied methodologies within each generic technique. Published estimates of seed bank densities should therefore always be considered within strict limits of interpretation. Deficiencies in sample size may preclude accurate assessment of seed densities and differences in methods of analysis make comparisons between different studies questionable.

Dynamics of the weed seed bank

Inputs to the seed bank

The seed bank is in a constant state of flux. Some species are able to disperse over great distances by a variety of mechanisms before they enter the seed bank. They may be dispersed from adjacent sites or habitats, by mechanical (wind, water or machinery) or animal (attached to fur, passing through the gut or moved by animals caching food stores) means. However, many studies conclude that the majority of weed species shed their seed close to the maternal plant, where they then go on to become incorporated into the seed bank. The seed bank is therefore being replenished regularly. The major periods of influx depend on the seed dispersal time of the dominant weed species within the local population. A species such as *Stellaria media* that can emerge throughout the year has the potential to shed seed continually all year round. Species like *Solanum nigrum,* which have a limited period of emergence, will show a much more restricted annual addition of seeds to the seed bank during the late summer. A number of different methods of incorporation of seeds into the seed bank have been identified, including earthworms, mammals, insects, rain and frost. However, the principal source of seed incorporation and redistribution within the soil, and between field and farms, is farm machinery (see section on 'Spatial distribution').

Seed losses, longevity and ageing

Once seeds have entered the seed bank they are at risk of death from various factors such as predation (by birds, bats, small mammals and invertebrates), attack by pathogens and microorganisms, natural physiological ageing and germination, both successful and fatal (Fig. 3.2). For many species, deeper burial increases the longevity of seeds in the soil, but studies have not been able to assess the true magnitude of losses due to the interaction of other factors. For example, germination is known to be a major source of loss of seeds from the seed bank, but it is difficult to separate losses due to ageing, attack by microorganisms and fatal germination since all result in the degeneration of the seed.

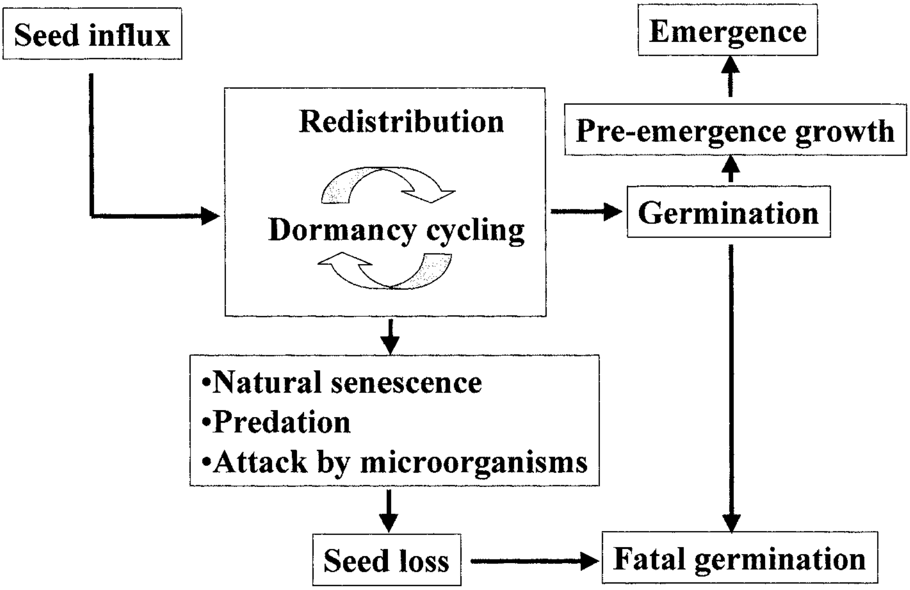

Fig. 3.2 Simplified diagram of the dynamics of the weed seed bank.

Seed predation may significantly reduce seed numbers in the seed bank, but it is an area that is largely unexplored and therefore often underestimated in dynamic seed bank models. It is likely that species composition, density, habitat, microhabitat and season all interact to modify seed numbers lost to predation. Cultivation will modify losses since seeds left at the surface are more accessible to predation than those buried, although there is some evidence of ingestion by earthworms, ants and slugs. In a study in Sweden, losses up to 92%, 84% and 83% observed for *Fallopia convolvulus*, *Chenopodium album* and *Thlaspi arvense* respectively were thought to be attributable to predation alone. Microorganisms, such as soil bacteria and fungi, can also destroy seeds through enzymes or toxins. The microorganisms can act either through inhibition of germination itself or by directly destroying the seed structure and contents.

Although larger-seeded species have greater food reserves, it is the smaller-seeded species that tend to form persistent seed banks. There are many reasons for this, including evidence that predators select for seeds of a given size. Both the lack of nutritional reward and the difficulty in finding the less conspicuous smaller seeds offer these seeds some protection. Small, round seeds may also become incorporated into the soil with greater ease than larger, more awkwardly shaped seeds. A relationship between seed weight and variance in linear dimensions has been proposed as an indicator of persistence. Compact seeds were found to be persistent whilst those above a critical variance in their dimensions were short-lived. Although this relationship is a simplification of a number of interacting factors, it offers a guide to the relative persistence of seeds in the seed bank.

As seeds age, this is sometimes expressed in the longer time necessary for germination to take place. However, in practical terms the age profile of a typical weed seed bank will generally be dominated by recently incorporated seeds. Therefore, it is unlikely that yearly emergence patterns are appreciably affected by the older, slower-germinating seeds. The reduction in germination rate reflects greater repair leading to a longer lag phase from the time of imbibition through to radicle protrusion. In the soil, seeds will experience fluctuations from dry to wet, and during extended periods of dry conditions damage can occur to both the molecular structures and the structural integrity of membranes. During imbibition some repair can take place, but it is proposed that a seed will only be able to sustain a finite number of cycles of wetting and drying before food reserves become exhausted. At this point lesions to DNA and malfunction of the membranes will eventually become irreparable. The number of dormancy cycles a seed is able to undergo in its lifetime has also been linked to seed age. Many of the processes of seed ageing have been studied in, for example, defining the moisture and temperature requirements for the long-term storage and maintenance of viability in crop-seeds. The conditions advised for successful storage of temperate orthodox seeds are cool and dry, but these are not the conditions experienced by imbibed seeds in the soil. Advances in our understanding of these processes of ageing and longevity may shed light on some of the processes experienced by their wild counterparts in natural environments.

Measuring the rate of seed loss

The seeds of some species are naturally short-lived, whilst viable seeds of others such as *Chenopodium album* have been found on sites known to have been undisturbed for over 1700 years. From this we can infer that there is the potential for great longevity in this species. However, these unrealistic situations show only maximum persistence and do not reflect the normal longevity of seeds of weed species in disturbed arable habitats. Little work has been done to determine the rates of loss for seeds of broad-leaved weeds in arable systems with disturbance. A study made at Long Ashton in the UK showed a rapid decline in seed numbers within the first few days of incorporation, probably due to predation and disease. Thereafter three broad-leaved species, *Galium aparine*, *Stellaria media* and *Papaver rhoeas,* were classified as having the three different strategies of negative exponential, gradual and long-term persistence.

Different approaches have been used to describe these rates of seed loss in the form of survivorship curves. A negative exponential (Deevey type II) curve has been shown to be well suited to the decline of seeds in arable soils in the UK. This type of decline illustrates that the seeds are under continuous threat of death and this probability remains constant over time. In contrast, a few species have demonstrated a slow initial decline followed by a rapid loss in the numbers of surviving seeds (Deevey type I).

Negative exponential, rectangular hyperbola and linear models, amongst others, have all been used to describe the survivorship of seeds. What is striking in all these studies is the lack of ability in these models to describe satisfactorily the variation in survivorship from one year to the next. Differences in weather, microclimate and predation pressure all contribute to the year-to-year variation in survivorship. Hence, whilst these models give an indication of patterns of loss over time, as yet we still do not know enough of the biological interactions between these factors on a site-specific basis to quantify and predict seed loss accurately.

Dormancy

Classifications

Seed dormancy is a potentially huge subject, itself worthy of a book, and comes in many forms with numerous definitions and categories. The simplest definition of dormancy is ‘a barrier that prevents germination when conditions would normally be favourable’. It is one of the most important features of weed-seed bank dynamics and provides a mechanism by which weed seeds can extend their longevity in the soil. They are able to avoid germination during unfavourable conditions and go on to capitalise on times when the environment is suitable. Dormancy is sometimes interpreted as an on/off switch; however, it has been shown that it is actually expressed on a continuous scale. For example, changes in dormancy are frequently observed as a gradual change in the width of the temperature range in which seeds can germinate.

Freshly shed seeds of many weed species will not germinate, regardless of incubation temperature. These seeds are said to have primary (or innate) dormancy. Primary dormancy is an indication of an immature embryo and the need for further development (or after-ripening) to take place in the seed. It is a mechanism that prevents precocious germination in the maternal plant, allowing time for the seed to be dispersed.

Primary dormancy is influenced both by the environment and by the genotype. Studies in *Avena fatua* have concluded that as much as 50% of variation in germination can be attributed to genetic rather than environmentally based differences in dormancy behaviour. Intraspecific variability in dormancy behaviour has been shown to persist even after winter after-ripening. Many studies of weed dormancy and germination ecology fail to look at more than one population; hence this source of variability is often overlooked. An exception was a study made in Scotland which looked at 18 populations of *Chenopodium album*. Maternal effects related to climatic differences during seed development, maturation and collection were controlled by multiplication of seed in a common environment. It was demonstrated that variations in the rate of dormancy relief, combined with different temperature optima for germination, resulted in a range of interpopulation differences in the subsequent germination ecology. Similar results have been found in *Poa annua*. Genetic models for dormancy may provide insight into this variability. Such models have already been proposed which include a genetic index to incorporate the proportion of dormant and non-dormant alleles in a field. This has been done for *Avena fatua*, where molecular markers have been identified for dormancy quantitative trait loci (QTL).

Primary dormancy is gradually lost and the seed then experiences what is known as conditional dormancy. At this time an increasing proportion of seeds in a population will be able to germinate, at first over a narrow range of temperatures. As conditional dormancy is lost, more and more seeds will be able to germinate over an increasing range of conditions. This loss of conditional dormancy is expressed not only in the numbers of seeds that become able to germinate in a population, but also in an increase in the rate of germination for some species. Eventually a point is reached where the maximum number of viable seeds in the population are able to germinate over the full range of environmental conditions for that species and the population is then described as non-dormant.

Many weed species are able to cycle between the non-dormant state through conditional dormancy back to a state of full dormancy (secondary dormancy). This is because the majority of weed seeds have a form of dormancy, known as non-deep physiological dormancy, that allows this cycling process to take place. Secondary dormancy and non-dormancy are the two extreme states of the continuum of dormancy. Some species never enter full secondary dormancy and some remain non-dormant throughout the year.

Sometimes the terms 'induced' and 'enforced' dormancy are also used with reference to weed seeds. Generally this terminology has become less common, since 'induced dormancy' broadly overlaps with the term 'secondary dormancy', i.e. it refers to a previously non-dormant seed re-entering dormancy. Enforced dormancy is regarded as an environmental block to germination or inhibition of an otherwise non-dormant seed, i.e. the seed is in a microsite which does not supply the prerequisites for germination at that time. This form of dormancy is not to be confused with a block within the seed itself, and is sometimes referred to as quiescence.

Dormancy behaviour and germination ecology

Dormancy and germination ecology are intrinsically linked, with germination periodicity being the expression of the underlying dormancy cycle of a species. Two basic categories of dormancy-breaking and germination ecology are evident in arable weeds: those species with seeds requiring warm temperatures during the summer months to break dormancy, and those requiring winter chilling to break dormancy. In general the dormancy-breaking process takes place during the season unfavourable to the growth and successful reproduction of that species. However, some species do not show such pronounced seasonal periodicity (e.g. *Stellaria media*) or show intermediate behaviour (Fig. 3.3).

For obligate (strict) winter annuals like *Lamium purpureum*, a period of dry after-ripening is required during the warmer dry summer months so that dormancy is gradually lost by autumn, resulting in a flush of germination. The plants are then able to flower and set seed in the spring or early summer. In facultative winter annuals (e.g. *Capsella bursa-pastoris*), some seeds in the seed bank behave as obligate annuals but the dormancy status of some seeds also allows germination in the spring, after which they behave as short-lived summer annuals.

Summer annuals (e.g. *Chenopodium album* and *Polygonum aviculare*) lose dormancy over the winter months following a period of chilling (stratification). Gradually, as the temperature of the spring environment reaches the range required for germination, a flush of spring emergence is observed. If there are other factors limiting successful germination at this time, e.g. seeds requiring light stimulus are buried too deeply, then they re-enter dormancy over the summer months. These seeds once again require a period of winter stratification before they have the opportunity to germinate in the spring of the following year.

Cues for flowering in both summer and winter annuals are also frequently correlated with the underlying dormancy patterns, since synchronous flowering is necessary, particularly for inbreeding species. Similarly, dormancy strategies offer an avoidance tactic for a weed species to maximise establishment success in the habitat from which it originates. Recent studies have shown that in some cases a winter chilling requirement for breaking dormancy is more closely correlated with habitat than with species. For example, species at risk of severe winters tend to have a long chilling period to release dormancy and subsequently a slow response germination rate at low temperatures to avoid the risk of frost.

Modelling dormancy

The now-familiar periodicity tables for common agricultural weeds are still as useful today as they were in the 1980s in that they provide a general guide to the

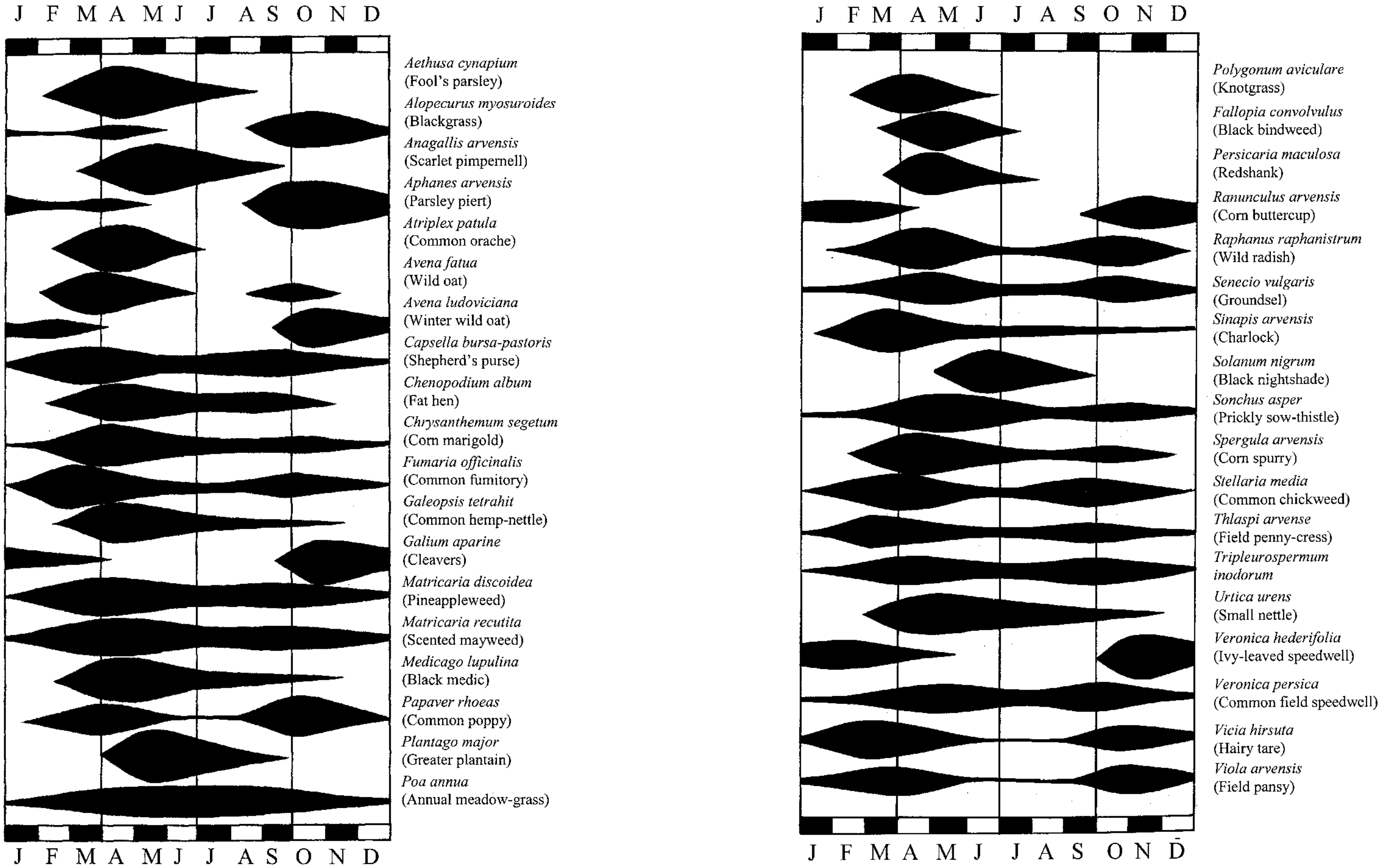

Fig. 3.3 Germination periods of some common annual weeds. A greater width of the bar reflects greater germination. Reproduced from Hance, R.J. & Holly, K. (1990) *Weed Control Handbook*, 8th edition, with kind permission of Blackwell Science Limited.

underlying dormancy cycles and germination flushes of weed species. Traditional physiological methods of studying dormancy are confounded by the difficulty of separating the germination and dormancy processes. However, advances made in seed science in recent years are improving our understanding of the physiology of these cycles in the weed seed bank. For example, although the way seeds actually perceive temperature is still not well understood, it has been suggested that it is associated with changes in membrane fluidity.

Temperature and water potential appear to be the two primary factors determining dormancy cycles. For example, dormancy loss has been shown to be associated with an ability to germinate at lower water potentials, i.e. at a more negative mean base water potential. A recently developed mathematical relationship for the annual grass species *Bromus tectorum* successfully described variability in germination time courses during the after-ripening process. This was achieved by simply altering the parameter of mean base water potential whilst holding all the other parameters in the relationship constant. These studies have demonstrated that laboratory-derived models of dormancy loss can be applied successfully to field situations under fluctuating temperature and moisture regimes.

Models based on thermal time have also proved to be increasingly successful in predicting the timing of loss and induction of dormancy. These models have been less successful, however, in predicting actual numbers because of the population variability in dormancy described above.

Germination

Gap and depth detection

A flush of emergence in the field is not always observed or may be significantly reduced in magnitude in spite of apparently ideal timing for germination in terms of the seeds' dormancy status in the seed bank and germination conditions in the environment. Vertical gradients in soil micro-climate, e.g. in water availability, temperature and light, occur in the field, so that one of the major factors influencing the success of weed seed germination and subsequent emergence is the seed's position within the soil profile. Many weed seeds are thought to be able to perceive and respond to these gradients so that germination is prevented at depths from which the seedlings cannot emerge. A simple example is that a light-requiring species, such as *Matricaria recutita*, cannot germinate unless the seed is at or near the soil surface. In addition, seeds that are deeply buried are insulated against the diurnal temperature fluctuations which occur closer to the soil surface and that are needed for germination. Responses to alternating temperatures in this way may also offer a method of gap detection for seeds. Above-ground vegetation modifies the environment which a seed perceives, and therefore its germination response. Established vegetation, which could pose future competition for resources, also filters light and so alters the quality perceived by seeds at or near the surface of the seed bank.

Modelling germination percentage and rate

In well-prepared horticultural seedbeds, soil moisture and temperature are likely to be the major determinants of seed germination patterns. Hydrothermal time is a concept which provides a basis for describing such patterns and has been extended to crops such as lettuce (*Lactuca sativa*) and tomato (*Lycopersicon esculentum*). Hydrothermal time is a combination of thermal time above a base temperature and hydrotime above a base water potential. A simple model of emergence based on threshold water potential and temperature has been shown to describe the varying patterns of seedling emergence in onion (*Allium cepa*). More recently, modifications of the hydrothermal time concept have been proposed to demonstrate that threshold germination models can be used to predict successfully emergence of carrot (*Daucus carota*) in variable field conditions.

There are only a small number of examples where these modelling concepts, originally developed to predict germination of commercial crop seeds, have been applied to describe the behaviour of weed species. The germination time courses of *Orobanche aegyptiaca*, *Chenopodium album* and *Stellaria media* have been successfully described in this way. An interesting observation for *Chenopodium album* and *Stellaria media* is that the temperature optima for maximum percentage germination and for the rate of germination were different. For both species, the rate of germination increased beyond the temperature for maximum percentage germination. An ecological adaptation that has been proposed for this difference might be the need for rapid germination and establishment of a small proportion of the population at these high temperatures in order to exploit conditions where the seedbed may be drying out.

Emergence

Studies on the post-germination/pre-emergence phase have found that whilst germination makes the greatest contribution towards the exact timing of an emergence event, the pre-emergence growth phase can have a major effect on the number of seedlings emerging due to post-germination death. The period of pre-emergence growth will also influence the spread of the flush of emergence because of the variations in the time required for seedlings from different burial depths to reach the surface. Therefore it is likely that, as with crop species, the temporal spread and magnitude of a flush of emergence is heavily influenced by this phase. In addition, weed seeds are typically variable in their vertical distribution in the soil profile; this emphasises the importance of taking burial depth into account when determining the temporal spread of a flush of weed emergence.

Emergence as a function of burial depth

Each species is known to have a characteristic emergence response to burial depth and models have been developed that describe this for a range of species. Successful emergence is dependent on a combination of suitable soil structural properties and the presence of sufficient reserves in the seed to sustain growth. It is generally accepted that larger seeds are able to emerge successfully from greater burial depths because of their greater food reserves. Recent work has led to the development of preliminary empirical models that predict the emergence of common arable weed species from a range of burial depths. These depth response models were generated using observations of seeds buried in narrow bands at known depths in a sandy loam soil. For *Chenopodium album* and *Polygonum aviculare* shallow burial promoted emergence, whilst for *Tripleurospermum inodorum* and *Veronica arvensis* a sharp reduction in emergence was observed with increasing depth of burial. A study in the US confirmed these two basic patterns in emergence response to increasing depth following analysis of a number of similar data sets. It was noted in this study that whilst half the data sets showed a monotonic decrease in emergence with increasing depth, the others had a non-monotonic response in which shallow burial increased emergence but deep burial reduced emergence. The Fermi–Dirac distribution function has also been used to describe the emergence response to depth for *Bromus tectorum*, *Sorghum halepense* and *Malva pusilla*. This function is a re-parameterisation of the logistic function and effectively has the same shape as the standard probit curve. These empirically based models give a probability of emergence, but they neither provide information on the proportion of seeds that germinate at a given depth but fail to reach the surface, nor do they explain why.

Physiological models of the post-germination pre-emergence growth phase

It is generally accepted that there is greater weed emergence in finer seedbeds. This is because the effect of soil aggregate size and seedbed preparation has the same implication for weed establishment as it has for the uniform establishment of the crop. It has been hypothesised that greater force may be required for pre-emergence growth in a cloddy soil compared with a fine tilth. However, this relationship is complex and it has been suggested in some studies that there can be advantages to cloddy soils in that they provide routes for the penetration of light and air. A study in the UK showed that the smaller-seeded *Alopecurus myosuroides* and *Stellaria media* were more sensitive to sowing depth and clod size than the larger-seeded wheat and *Galium aparine*. It was concluded that, far from inhibiting emergence, the coarser aggregates, as opposed to the fine tilth, tended to enhance seedling emergence.

Research on pre-emergent shoot growth has focused largely on cultivated species but may ultimately help us to understand the physiology of shoot development of weed seedlings in different soil types and strengths, using factors like mechanical and water stress. A physiological model has been already developed in the Netherlands for *Polygonum persicaria*, *Chenopodium album* and *Spergula arvensis*. The model used the parameters of soil penetration resistance, burial depth, seed weight and temperature to drive the pre-emergence growth stage of seedlings, and good predictions were achieved. The relationships appeared to be stable over the three species, suggesting that the same physiological principles governed growth. The study found that, given identical germination times, seedlings of *Chenopodium album* were consistently the earliest to appear at the surface, giving them an obvious competitive advantage.

Modification of the seed bank

The dynamic nature of the seed bank means that there are many possibilities for manipulation within an agricultural system by influencing germination or emergence or by directly affecting the viability of seeds. The ecophysiological processes responsible for these changes have been outlined above and this section will detail the practical applications of manipulative strategies. These can involve the type and timing of cultivation (if any), stubble management, time of crop drilling, fallowing, solarisation, mulching, soil sterilisation, residual herbicides and the use of dormancy-breaking stimulants. Other management strategies such as choice of rotation and the introduction of genetically modified crops affect the seed bank, but only indirectly through the impact on plant population dynamics, and are therefore not considered here.

Modifying dormancy and germinability of seeds

A number of seed bank management techniques act directly on the germinability of the weed seeds by either stimulating or suppressing germination. Synthetic gibberellins have been used to enhance germination in species such as *Solanum nigrum* but with variable success in the field. Techniques such as application of solarisation, chemical sterilants, steaming and dry heat all kill the weed seeds *in situ*. Mulches act by modifying the microclimate experienced by the seeds whilst in the cases of living mulches some plant residues can also have an inhibitory effect on germination. The practical details of many of these methods are described elsewhere within this edition. A novel method to deplete the seed bank selectively has been the application of dormancy-breaking compounds such as smoked water. The method has been demonstrated in Australia with native and introduced weed species, but as yet it is not understood how compounds in the smoke affect the seeds.

Modifying rate of loss through cultivation

Altering the position of seeds within the soil profile and changing the frequency of disturbance are two ways in which rate of decline due to germination can be directly modified by man. Cultivation influences the rate of decline chiefly through increased germination potential. Seeds are brought to the soil surface, where they may be more likely to receive the temperature, oxygen ratio, light and other conditions necessary for germination. Cultivation may also release the seeds from potential germination-inhibiting gases and metabolites. However, regardless of frequency, cultivation will only modify the magnitude of a flush of weed germination and emergence at any given time during the year, and even then only when there is adequate moisture. The species content of this flush of emergence itself will ultimately depend on strong seasonal periodicity governed by underlying dormancy cycles.

In the absence of seed return, soil seed bank densities decrease exponentially over time, but decline is more rapid under cultivation. Studies at HRI Wellesbourne UK (previously the National Vegetable Research Station) reported annual germination rates of 1% of the seed bank where soil was undisturbed, but 5% after a single cultivation, although it must be remembered that germination rates vary widely between sites, years and species present. Generally, the rate of decline increased with the frequency of cultivation, up to 9% annually on plots cultivated four times, but for some species there was no difference, presumably because of interactions between cultivation date and periodicity of germination. The importance of cultivation in reducing weed infestations has long been recognised; in the past, fallowing, with repeated cultivations through the year, was an important part of weed management strategies. With the introduction of herbicides and in the current economic climate, fallowing is not a financially viable option. However, set-aside is a form of fallow with specific management requirements, which can be a useful weed control strategy if managed carefully so as to avoid seed return.

The type of cultivation can significantly affect the seed bank by influencing the vertical distribution of seeds in the soil profile. Ploughing results in the most effective burial of seeds and work at Long Ashton Research Station, UK, reported that ploughing to 20 cm buried over 90% of surface-sown seeds to a depth of at least 10 cm. However re-ploughing is much less efficient at bringing buried seed back to the surface. Studies comparing the effects of different tillage systems on seed bank density have recorded lower densities under ploughing regimes and higher under no-till systems. Ploughing, as opposed to non-inversion tillage, is important in the control of weeds, but particularly grass weeds such as *Anisantha sterilis* and *Alopecurus myosuroides*. These are short-cycle species; the seeds have relatively weak dormancy and only a small proportion of seeds survive for more than one year in the soil. Ploughing therefore puts freshly shed seeds below the depth from which they can emerge, and only a small proportion remain in the following year to be brought back to the surface if the site is re-ploughed. Conversely, ploughing can perpetuate infestations of broad-leaved species which form persistent seed banks that survive for many years in the soil. Ploughing has been shown to favour *Chenopodium album*, *Polygonum* spp. and *Anagallis* *arvensis*, enforcing dormancy and ensuring long-term survival of the species by dispersal over time.

Most species exhibit the periodicity of germination described above, and this can be exploited to enhance weed control. Autumn-sown crops are associated with winter annual species which germinate in the autumn and have a competitive advantage over spring germinators. Species which germinate in the autumn will be destroyed by soil disturbance associated with drilling of a spring crop, allowing summer annuals to flourish. The drilling date can also have more subtle implications. Delayed drilling of autumn cereals can achieve significant control of *Anisantha sterilis*, which only germinates over a relatively short period of time in the autumn. However, *Alopecurus myosuroides*, which germinates through the autumn and into early spring, is not controlled by simply manipulating the drilling date by a few weeks. Timing of cultivation within the diurnal cycle may also be important in weed management. Because many seeds are stimulated to germinate by exposure to light during soil disturbance, cultivating in the dark has been proposed as a method to reduce or delay germination of weeds. However, in practice this technique has rarely proved effective and its importance will depend on factors such as species present and soil type.

Management of stubble after crop harvest is very important in weed management and can reduce pressure on herbicides, particularly where weeds are resistant. However, studies have only been made for a few key species. Stale seedbeds, where seedbed preparation is completed several weeks before drilling, can stimulate seeds to germinate which are subsequently destroyed by activities associated with drilling. However, the effects of stubble management vary with species, resulting in conflicting prescriptions for weed management. Work at IACR – Rothamsted, UK, demonstrated that control of volunteer oilseed rape was greatly improved if seeds shed at harvest were left on the soil surface for at least two weeks before incorporation. Light sensitivity was not induced in seeds at the surface and persistence of the seeds was therefore reduced. However, it is important to bury seeds of *Anisantha sterilis* soon after harvest. In this species, exposure to light inhibits germination and therefore reduces the period of time between cultivations and drilling when germinated seedlings can be destroyed. The effects of stubble management, however, interact with other factors such as weather conditions and straw management.

Modelling the weed seed bank

Problems

Whilst much of the basic biology of seed banks has changed little since the previous edition of this book, major advances have been made in the area of modelling. We have seen how modelling has been used to describe and predict dormancy, germination and emergence, to name but three elements of seed bank functioning. Some models have been combined to simulate the dynamic environment of the seed bank. The success of all of these models in describing what is observed in real life varies greatly. Their failures highlight the fact that, as yet, our understanding of the interactions of many of the biological processes involved in seed bank dynamics has a long way to go. Over-complex and over-parameterised models may not provide the long-term answers required in practice by growers; instead, simple robust versions need to be developed. Lack of reliable and long-term weather forecasts in sufficient detail, problems in representative sampling and the need for efficient extraction methods outlined above also provide hurdles to the practical application of many seed bank models at present.

Opportunities

In relatively short-term studies it is often difficult to identify the factors that are important in determining weed emergence patterns. The results from longer-term studies, when averaged over time and using the ever-increasing power of computer modelling and analysis, may provide the basis for empirical models predicting the patterns of annual emergence. There are already examples in weed biology where certain meteorological events, such as the first date on which a threshold soil temperature is exceeded, can be significantly linked with emergence. This type of empirical approach has been used successfully to predict the onset of a range of crop pests and diseases. Some simulation models for the timing of weed emergence have used parameters such as soil moisture and temperature in combination with laboratory-derived or estimated thresholds as their basis.

A better understanding of the germination behaviour of weed species in relation to cultural and meteorological events presents a number of opportunities. For example, many non-chemical weed control options directed at the seed bank, such as the use of mulches and cultivation techniques described earlier in this chapter, fail to produce reliable results simply because of haphazard timing relative to the underlying dormancy cycles. Therefore, from a non-chemical control point of view, the benefits of predicting dormancy cycles are huge. This information can also be used to target the timing and maximise the efficacy of strategies such as mechanical weed control. Similarly, the relative emergence times of the crop and weed are important factors in determining the critical timing of weed removal, as has been illustrated in a number of competition studies. Simulation of both weed emergence and crop–weed competition can therefore contribute to making the most effective use of limited weed control resources. The potential for using information about the timing of emergence for weed management is already being realised in the form of forecasting software in the USA. Used in combination with bioeconomic models for weed management, the resulting decision support systems could provide powerful tools for both the grower and scientist.

Understanding the factors that control not just the timing but also the magnitude of weed emergence may also help us to manipulate seedbed conditions. A wide range of different weed seed bank distributions and compositions could be modelled using a range of different tillage operations. One example where this could be useful would be to maximise the stimulation of emergence when using a stale seedbed. Modelling the vertical distribution of weed seeds and how this can be manipulated could also be used to target particular problematic species or even populations within a species, through exploiting dissimilarities in emergence characteristics. Studies in the USA have already demonstrated that selective cultivation can be used to modify emergence of *Abutilon theophrasti.* Alternatively, cultivation operations could be used to reduce weed emergence by placing seeds in the lower part of the profile.

Dynamic models

Dynamic seed bank models may be used to predict the long-term outcome of weed management strategies, by identifying shifts in weed flora, composition and spatial position. Some management strategies based on the seed bank (e.g. established techniques like the use of stale seedbeds and avoiding volunteer oilseed rape problems through appropriately timed post-harvest cultivation) can reap direct rewards. It is important to note, however, that many seed bank strategies are likely to be much less immediate in delivering their benefit. In these situations in particular, the benefits of predictive seed bank models that enable us to take a more informed look into the future are apparent. Above all, the greatest benefit likely to be gained from seed bank modelling studies is the acquisition of a learning tool to help us to discover new ways of modifying the seed bank to our advantage and to understand the complexity of the processes involved.

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Chapter 4
Weed Population Dynamics

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Introduction

The occurrence of a single weed plant is not important to the yield of the crop it grows in. However, with uninterrupted growth the single weed plant can give rise to a large weed population which can greatly reduce future yield. This justifies the management of even small populations in advance of their producing economically important yield reductions. The calculation of weed thresholds to trigger crop management interventions illustrates the importance which crop managers place on the restriction of weed population growth.

The growth of weed populations can be very rapid. This chapter covers the main features of the dynamics of weed populations. The generation cycle from seed to seed is briefly described. The potential for a rapid rise of population numbers and the features of plant biology which contribute to this are considered. Models of how populations function are discussed in the context of how these models help our understanding of weed population dynamics and our knowledge of which management options might be successful.

In this chapter the main examples will be of annual weeds, i.e. those that go from seed to seed within a year. These may be summer annual species, such as wild oats (*Avena fatua*) or knotgrass (*Polygonum aviculare*), which overwinter as seeds in the soil and germinate in spring. In contrast, winter annuals such as blackgrass (*Alopecurus myosuroides*) or cleavers (*Galium aparine*) can germinate in autumn and overwinter as seedlings. The population dynamics of perennial species, such as couch (*Elytrigia repens*) or docks (*Rumex* spp.) are rather similar except for the additional means of small-scale local consolidation at a site through vegetative reproduction. Thus, annual increases in populations of above-ground shoots of perennial plants result from both sexual reproduction by seed and vegetative, clonal spread from buds.

Life cycles

The population dynamics of weeds can be considered at two different scales. First, there is the annual cycle of reproduction, which is the means whereby one seed produces more seeds. Then, a sequence of annual cycles of reproduction can lead to rises in population levels over the years or, if sound weed management is implemented, the population may decline over time.

From the weed's point of view, a successful annual reproduction cycle (Fig. 4.1) results in a population of fresh seeds being shed to the soil (the seed rain), where it is incorporated into the weed-seed bank (Chapter 3). Crucial for the survival of the species is the ability of these seeds to germinate and produce new plants which may progress to reproduction. The initial invasion of naturally disturbed environments involves 'pioneer species', which have a set of common characters reflecting their survival in sparsely distributed populations. The creation of a seedbed into which to sow crop seeds represents for other species a great disturbance of their environment. Not surprisingly, many successful weeds are also pioneer species and the characteristics listed for an ideal weed are the characteristics of pioneer species (Baker's Rules – Chapter 1). This is generally true of both annual and perennial weeds. Environmental conditions at the scale of the microsite occupied by the individual seed in the soil determine the progression from seed to seedling. In many wild plants, including weeds, not all the seeds germinate at the same time. This may be because not all seeds encounter favourable germination conditions but also because some seeds remain dormant for longer. The evolution of a range of germination times represents an evolutionary strategy which reflects the ability to maintain a population in a changeable habitat where established plants may be subject to a 'catastrophe' which prevents reproduction. Were this to happen to a whole cohort of seedlings produced from the complete seed bank, then the species would become extinct at that site.

The phrase 'seedling establishment' is used to describe the period from emergence of the seedling shoot above ground to the time at which it becomes independent of seed reserves. In this phase the tender seedlings are very attractive to pests and are easily damaged.

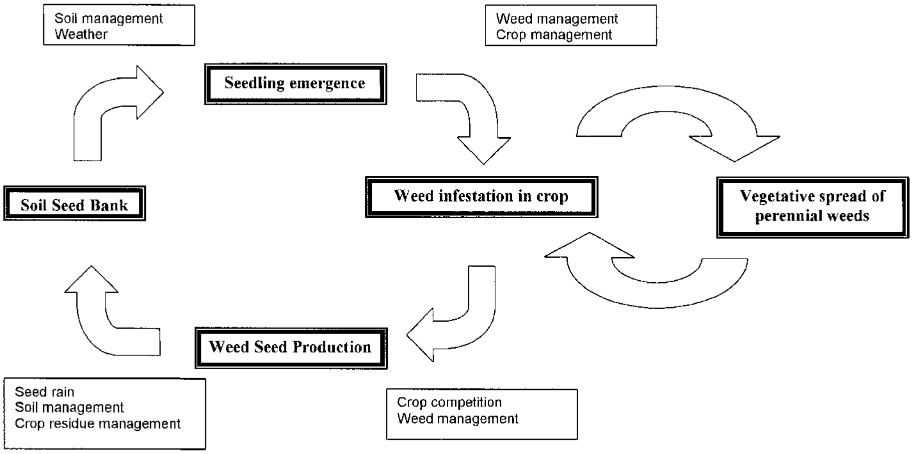

Fig. 4.1 The annual reproduction cycle of weeds and the factors which influence the transfers between stages.

The onset of reproduction is an important point in the weed life cycle. It marks the start of the processes which culminate in the shedding of a new batch of fresh seed as seed rain to swell the weed-seed bank in the soil. The majority of weed management decisions focus on trying to prevent this and use cultural, mechanical, biological or chemical means to achieve it.

In perennial weed species there is an additional focus of trying to prevent the vegetative spread of individual existing plants. This radial spread can be considerable and represents the growth of an individual (i.e. a single genetic entity) and its success in occupying space. Species such as perennials, which occupy the same site for a long period, have evolved ways of exploring and exploiting their environment, e.g. by means of rhizomes and stolons which bear buds. Development of the plant is relatively plastic because only if the environment is suitable may the buds develop into aerial shoots with associated roots, thus creating a new 'individual' (termed a ramet) of the same genetic constitution as the 'parent'. Alternatively, vegetative organs may be detached and dispersed, as are the corms of onion couch (*Arrhenatherum elatius* var *bulbosum*). Soil management and cultivation are critical because they may only serve to divide the original plants into fragments, distribute them around the field and allow them to regenerate, thus spreading the infestation rather than containing it. Recourse to chemical and biological methods of weed management is usual for perennial weeds.

Sources of infestations

'One years' seeding, seven year's weeding' is an old farming saying which encapsulates two main ideas. First, that from small initial infestations, larger weed populations arise in subsequent years, and second, that the seeds survive for some time. The significance of the weed seeds in the soil is thus to create a continuing requirement for weed management. Chapter 1 has given details of the importance of clean seed in preventing the introduction of new weeds onto the farm or spread to a previously clean area. Natural seed dispersal is also important; this emphasises again the importance of preventing weeds from producing seeds which can replenish the soil seed bank. There is the fear that weeds growing in hedgerows may be sources of future infestation. Nevertheless, modern integrated weed management emphasises the beneficial effects of weeds either in supporting populations of organisms which are antagonistic to crop pests and diseases, or more generally as a component of wildlife and rural biodiversity (Chapter 5).

Weed seed banks

The weed seed bank in the soil is of central importance to weed management (Chapter 2). Various other chapters justify management measures in terms of a longer-term contribution to reducing the weed seed bank. For the weed species, the seed bank is the means of generating a new population, often of individuals with different combinations of genes because of sexual reproduction. The growing weed population is acted on by natural forces and by human intervention, which together determine the relative success of individuals in contributing offspring to future generations via the weed seed bank. Thus, the mix of genes in the population may change. If management measures change, then we would expect the number and proportion of genes which survive to change. This provides a potent force for the evolution of weeds, as we have seen in the case of herbicide-resistant weeds (Chapter 11). Because weed seeds do not all germinate simultaneously, the different degrees of dormancy lead to differing individual longevities. Thus, the weed seedling population may not represent just the offspring of seeds produced by successful (i.e. not killed) individuals from the previous crop season. In this respect the weed seed bank provides dispersal across time, or what has been termed an 'ecological memory' of offspring from individuals successful in many previous seasons which may have had different challenges from weed managers and the environment. Different species have different characteristic seed longevities and this determines whether they have a persistent or ephemeral seed bank. The longevity of seeds depends not just on species but also on the soil conditions. When seeds have been buried, cool moist soil conditions often impose a secondary dormancy and there are often fewer seed predators away from the surface.

Models of population growth

Studies of plant population dynamics have exploited various types of models to help understand the processes involved. Initial quantification of the demographic parameters of populations, i.e. births (new seeds), immigration (seeds dispersed into the site), deaths and emigration (seeds dispersed out of the site) permits some description of population dynamics through compiling a 'life table'.

The logistic model

The logistic growth equation has been much used to describe population changes over time (sometimes measured in generations) from initial colonisation, through rapid population rise at a maximum rate of growth (r), to a final equilibrium or ceiling population size (K) (Fig. 4.2). However, this assumes that population growth is continuous, that it eventually reaches a stable state and that the environmental conditions remain constant. However, in arable weed populations, reproduction is usually confined to one period of the year, the environmental conditions differ each year and they include management interventions designed to reduce the population size. Such weed management usually returns the population to a smaller size and may thus maintain it in the rapid growth phase.

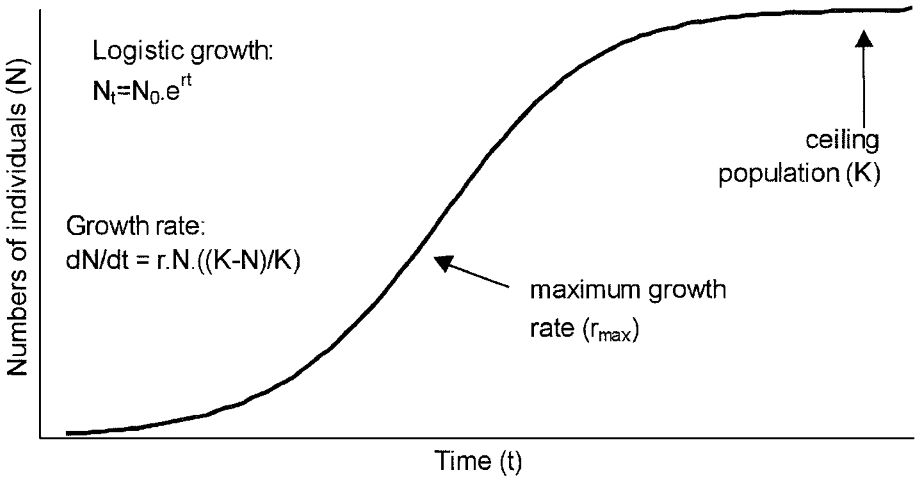

Fig. 4.2 Logistic growth curve.

Matrix models

Recognition that weed-seedlings may emerge at different times and that larger weeds probably produce more seeds has led to the development of matrix models. These aim to describe the transitions, or fluxes, between the life cycle stages of seeds, vegetative seedlings and reproductive plants (Fig. 4.3). Matrix models permit the estimation of effects due to altered probabilities of transition from one stage to another. This is useful because we can then examine the impact of weed management measures which would be expected to alter the transition probabilities, i.e. the survival from one stage to another. Matrix models can also deal with perennial species which both survive over a period of years and produce an annual cohort of seeds. They use life tables or demographic data to quantify the fluxes in the model. In the simplest models, annual surveys permit the identification of transitions between three classes or compartments, seeds, vegetative plants and reproductive plants.

The time at which a seedling emerges is a strong determinant of its survival, growth and fecundity (the number of offspring, seeds, which it leaves). Even small differences in seedling age may be magnified by competition; seedlings which emerge early do so into a relatively open environment, whereas later-emerging seedlings come into an environment already containing larger plants which have therefore already 'captured' some of the space and resources. More complex matrix models may divide the individuals into a number of age-cohorts or size-classes to recognise that older or larger individuals may have different likelihoods of surviving, reproducing or dying (Fig. 4.4).

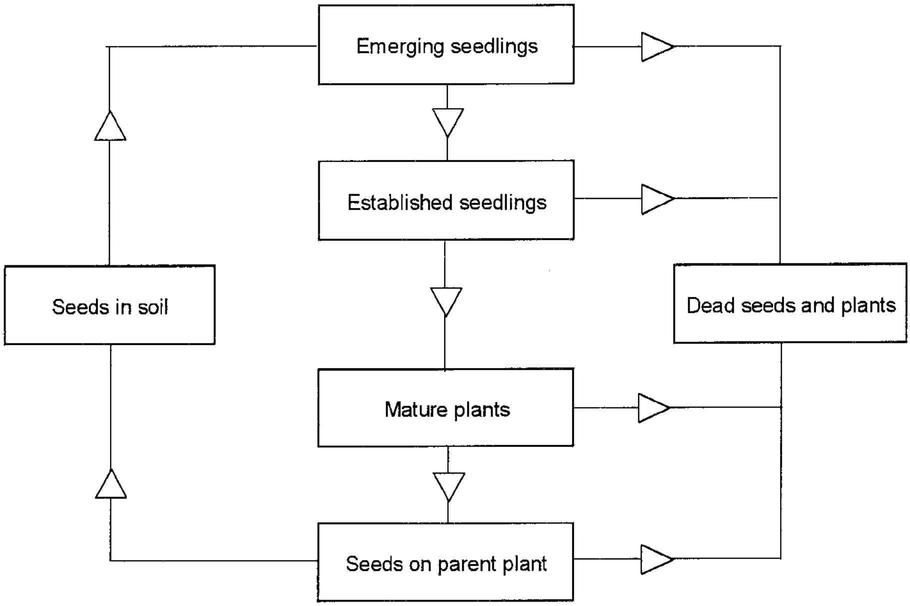

Fig. 4.3 A life cycle flow diagram. Arrowheads indicate fluxes, or transfers, between compartments.

Other features of populations

In mixed populations of crops and weeds, the agronomist is usually concerned to minimise the interference of the weed with crop growth. As other chapters emphasise, vigorous crop growth can make a valuable contribution to weed management. In other words, the presence of the crop suppresses weed growth and reduces seed production. Thus, models of weed population dynamics need to take account of the presence of a competing crop by incorporating the effects of interspecific interference.

When weed populations have developed to high densities, then each individual weed often interferes with the growth of another. This is to be expected; otherwise populations would increase indefinitely and there would be no defined ceiling population. As the plants in a dense population grow, some die. This density-dependent mortality influences the behaviour of future generations because it is usually the smaller individuals which die first. These are often the individuals which emerged later and by dying they contribute no descendants to the seed bank. Thus, in models of weed populations over time, intraspecific interference plays an important part in the regulation of dense populations.

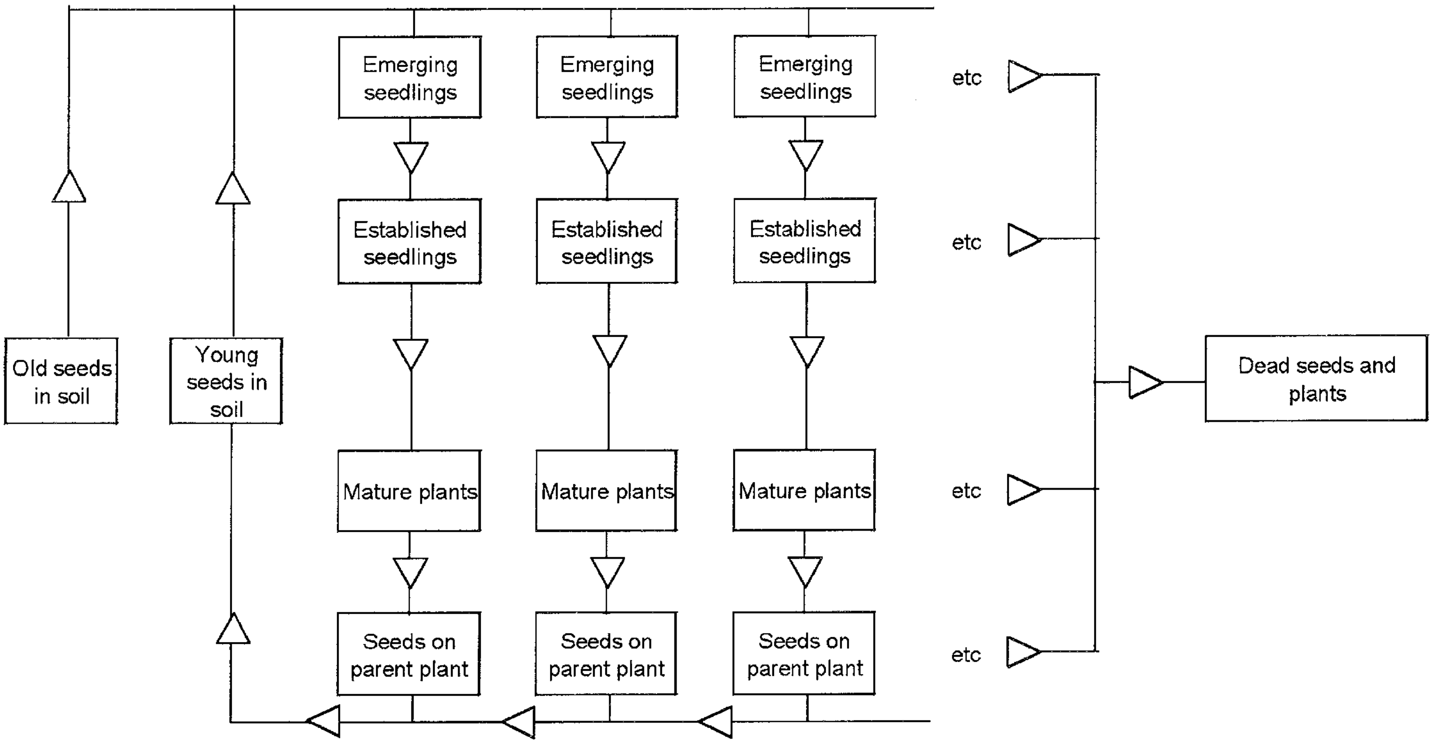

Fig. 4.4 A life cycle flow diagram including cohorts of seed ages and cohorts of seedlings. Each category has an individual flux to different compartments.

Characteristics of weed populations

Clearly, weed species which are successful on arable land are likely to have a high intrinsic rate of population growth (*r*) because the population can recover rapidly from disturbances. In contrast, the grassland environment can be considered as more stable, being less frequently disturbed and with a more complete vegetation cover. Success here is determined by long-term survival of individuals because weed species may have little opportunity for rapid population growth. Many grassland weeds are perennial. In these circumstances, the features of the environment limit population size, and these together determine its carrying capacity (the ceiling capacity, *K*). In a heterogeneous environment *r*, *K* and the distribution of the population over the mosaic of environmental variation all influence potential population size. Such considerations have led to the description of species on a scale from being *r*-selected to *K*-selected. Many of the successful annual arable weeds are towards the *r*-selected end of the range of population behaviour and exhibit characters common to populations of pioneer species. These characters contrast with the population behaviour of weeds in more stable environments, which are towards the *K*-selected end of the range (Table 4.1).

Table 4.1 Common population characteristics of *r*-selected and *K*-selected species

Population behaviour	*r*-selected species	*K*-selected species
Population size	Variable in time and space, often well below maximum (*K*)	Often stable, near *K*, re-invasion not needed to maintain population size
Plant environment	Variable due to weed management interventions, crop rotations and soil management	More stable or consistent management over a period of years
Survivorship	High mortality, particularly in early stages	Continuous morality, sometimes increasing with plant age
Life cycle	Often annual	Often biennial or perennial
Reproduction	Early onset, single reproduction period	Delayed reproduction, often repeated in subsequent years

An alternative classification of plant type is as competitors, ruderals or stress-tolerators. Competitors tend to respond to stress by rapid and large changes in leaf area and root surface area but have only a small proportion of the annual biomass allocated to seeds. Ruderals respond to stress by swiftly changing from vegetative growth to reproductive growth and have a large proportion of annual biomass devoted to seeds. Stress-tolerators show only small changes in morphology and growth, and a small proportion of the annual production is devoted to seeds. These descriptions represent extremes of plant behaviour and an individual species is likely to exhibit some combination of all the strategies. In particular some demographic characters of species are not fixed but differ according to the environment; this is particularly true of annual species. Many of the successful annual weeds behave as ruderals (e.g. *Chenopodium album*, *Poa annua*, and *Stellaria media*). Some successful grassland weeds are stress-tolerators, but also maintain a long-lived seed bank which allows colonisation of gaps in the vegetation or recruitment when the grass is ploughed for return to annual crops.

Using weed population models

There are two main reasons for constructing models of population growth. First, if we can build a model and then validate it (i.e. demonstrate that it bears great similarity to reality) then we clearly have enough knowledge to describe the species. The second reason is that we can use the model as a predictive tool to improve current weed management strategies and to develop new ones. Modelling the effects of different weed management systems on weed populations allows us to estimate the efficacy of each. Modelling may help us to discard ideas that seem unlikely to be effective and so save time and money in testing them in field trials. Because matrix models can incorporate different values for the 'fitness' (or ability to survive and produce offspring) of different classes of individuals, they can also be used to model and predict the outcome of weed management measures on herbicide-resistant weeds.

The accuracy of predictions from weed population models depends on how well we have been able to specify the quantitative fluxes contained in the models. True validation should test model predictions with independent data sets (i.e. data not used in developing the model), otherwise all that is being examined is the accuracy of the description of the data. Few weed population models have been tested in practice and properly validated. In many cases the prediction has only been checked for one or two seasons, despite the desire to use the model for long-term prediction of the fate of weed populations.

Inevitably, the values assigned to parameters in population models are estimates. Often these estimates are based on a limited number of sites or on only a few weed management regimes. Because different weed populations behave differently at different sites and in different years in response to the environment experienced (including crop, soil and weed management), we can only provide average values or, more usefully, limits of a range of values.

A major use of weed population models is as a tool to examine the effects of environment on population dynamics. In this context, environment for the weed is not solely the weather and the soil conditions, but also importantly includes management factors. Soil cultivation will influence the transfer of new seeds from the soil surface to a depth at which they remain dormant but can also bring older seeds to the surface where they may germinate (Fig. 4.5). Cultivation during the crop growing period is part of mechanical weed management and can kill a large proportion of a seedling population. Crop sowing date and sowing density should be incorporated into a model because they influence whether the seedlings are produced and killed before sowing or whether they emerge into the crop. Fertilizers also increase crop growth but may also benefit the weeds. Foliar application of liquid nitrogen to the crop may provide benefit to the crop species without benefiting the growth of shorter weeds and so it may help to skew competition in favour of the crop. Crop density can influence the intensity of crop/weed competition and hence the reproductive success of the weeds, which is clearly important for population dynamics. Other factors which influence the weed phase from seed shedding to seedling production are the extent of weed seed removal during harvesting and the influence of crop residue management and stubble cultivation. Eradication of barren brome (*Anisantha sterilis*) has been achieved by a single year of ploughing contrasted with high densities remaining on plots with minimum cultivation. All these factors need to be understood, quantified and built into a weed population model if the tool is to be useful in providing guidance on crop management systems which will reduce the impact of weeds.

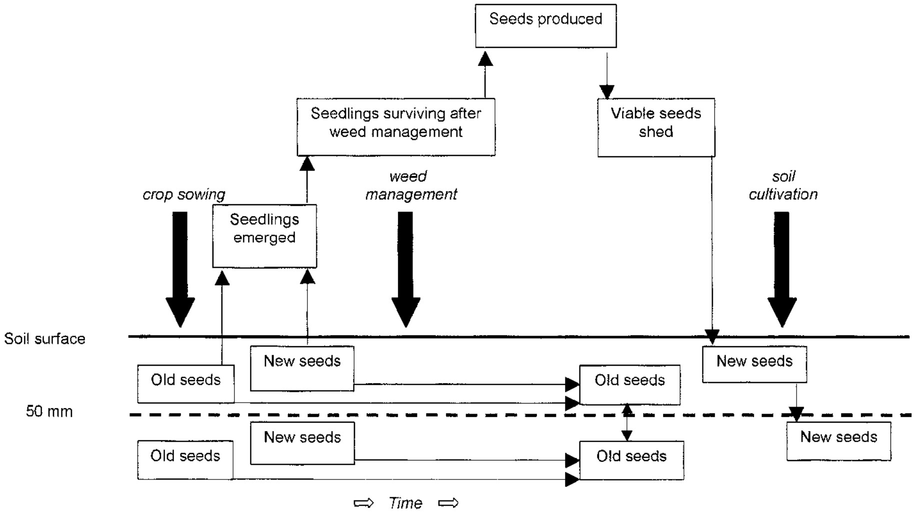

Fig. 4.5 Life cycle model for annual weeds, indicating where crop management may impact on population dynamics.

A realistic model of the population dynamics of a weed species, which incorporates quantification of the effects of soil, crop and weed management options, is a prerequisite for a sound decision support system (DSS; Chapter 16). We have much information and reasonable models for some of the most problematic and competitive weeds, but for many species we have little information.

Challenges for weed population modelling

A major difficulty for weed managers is that weeds are not distributed evenly across a field. Particularly in the early stages of an infestation, there may be isolated patches of weeds. Ignoring these can lead to a rapid build-up of the population of an *r*-selected species. In a *K*-selected species the patches may remain in a particular location for long periods of time. Locating and eliminating these patches can be time-consuming and costly. The option of treatment of the whole crop to manage one species present in patches is not economically or environmentally attractive.

Patchiness of weed distribution is to be expected. Although crop managers try to create an even habitat for crops, the soil and aerial environment are rarely consistent across a field. Large fields formed from the amalgamation of smaller fields are often easily identified by eye and in yield maps of fields. Removal of old walls, hedgerows and fences rarely removes the weeds associated with them. These variations in habitat and vegetational history often lead to large-scale heterogeneity in the environment. At the scale of the seed (the germination microsite) there may also be great heterogeneity, leading to patchy recruitment of seedlings. This patchiness in the environment may be introduced by crop management systems. The use of 'tramlines' in fields creates linear regions of more compacted soil. Most sowing systems lead to overlaps at the edge of the field with small areas being sown at either very low crop density or about double the average.

Many of our rare arable weeds, which are of considerable conservation interest and important for wildlife (Chapter 5), occur as isolated patches within fields. If we are to encourage such species, we need to understand the patch dynamics both over short periods (one year to the next) and over longer intervals (decades). Incorporating patch dynamics into weed management systems is a considerable intellectual and practical challenge.

Technology is being used to address the challenge of managing patchy distributions of weeds. Machine vision systems can be mounted on the front of a sprayer and used to control the release of herbicide so that it happens only when weeds are 'seen'.

Reality versus models

An important feature of real weed populations in the field is that they are rarely composed of single species. Our models of population dynamics are of single species and do not incorporate ideas of interference from species other than the crop. However, in many cases the weed management system can be designed to address the main weed species which are known to occur at this location (from a whole-farm to a within-field scale). The assumption is that the 'minor' weeds will remain at low levels or are inherently less competitive. One approach of both modellers and weed management advisors has been to distinguish the main important competitive weeds, such as wild oats (*Avena fatua*), blackgrass (*Alopecurus myosuroides*), cleavers (*Galium aparine*) or fat hen (*Chenopodium album*), but to group many weeds into a general class of 'broad-leaved weeds' (BLW) and treat these as one 'pseudospecies'. While this may be a reasonable approach for the more competitive crops such as cereals, in less competitive crops such as carrots or onions there may be a real risk that a population of any weed will reduce yield (Chapters 2 and 19).

Conclusions

Weeds exist as mixed-species populations within a crop population. The population sizes vary in space and time. Trying to describe the fluctuations in weed populations or their location is not easy because of these fluctuations and because of our attempts to manage weed populations. If weed population models are to be incorporated into decision support systems, then the predictions need to be robust and accurate to provide sound and practical weed management advice.

Key points

- Weed populations vary in space and time
- For the weed, the environment includes all the crop and weed management decisions
- Weeds frequently have a patchy distribution
- Weed population models are an attempt to summarise our knowledge and understanding
- Weed population models can be used as tools to help develop and choose weed management strategies

Further reading

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Chapter 5
Weeds and Biodiversity

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Biodiversity and biodiversity action plans

Almost all countries in the world are signatories to the Rio Convention on the Conservation of Biodiversity. The conservation of biological diversity is a stated aim of the UK Biodiversity Action Plan, which was drawn up as a result of the Rio Convention:

> 'To conserve and enhance biological diversity within the UK and to contribute to the conservation of global biodiversity through all appropriate mechanisms' [Anon., 1994]

Most countries now follow similar approaches to the conservation of biological diversity.

The reasons for the conservation of biodiversity are moral, aesthetic, social and economic. We steward other organisms for their intrinsic value and because species may be of benefit to human society and have economic value. A culture that encourages respect for wildlife is preferable to one that does not. Biodiversity can be easily lost but is difficult to regain, particularly if species are driven to extinction. Biodiversity, including genetic diversity, may provide economic benefits; even at the level of landscape, biodiversity may influence tourism and sense of place. Perhaps of greatest concern is that biodiversity has a role in the function of ecosystems, and erosion of diversity may thus ultimately result in damage to ecosystem function.

Within the UK, the Biodiversity Action Plan has identified a number of species that require conservation attention. Those of highest priority have their own Biodiversity Action Plan (BAP). In addition, some key habitats have been identified and have their own Habitat Action Plan. In agricultural areas, two Habitat Action Plans are of note, covering Cereal Field Margins and Species-Rich Hedgerows. Within each Plan, a statutory agency is identified as the leader and targets for management to maintain or enhance the species or habitat are published.

Weeds in the food chain

Plants are key components of terrestrial ecosystems, providing the primary production upon which food chains are built. The conversion into sugars of solar energy, CO_2 and water by photosynthesis in plants is the basis for plant growth. Different plant parts may then provide a range of resources for associated fauna: leaves and stems may be browsed, while pollen and nectar provide resources for pollinating insects; fruits and seeds are important food for a large number of organisms. Plants have other functions as well as providing food for herbivores. They provide cover, reproduction sites and structure within habitats. The effects of plants within ecosystems may also be to provide heterogeneity in space and time. Under successional change, plants may modify the environment. Plants also form a substrate for bacteria, fungi etc., both above ground and in the soil, where the rhizosphere supports many interactions.

In agriculture and horticulture, weeds are plants that interfere with production, either as crop competitors or by affecting harvesting, storage or crop quality. However, even in agroecosystems, so-called non-crop plants or weeds may play a role in the function of the ecosystem and in supporting many other species. Plants may affect soil processes, nutrient cycling and trophic interactions via fauna, flora, microflora and fungi. Each of these may be associated directly and indirectly with plants. The fauna can include invertebrates, reptiles, amphibia, mammals and birds. As an example, the grey partridge (*Perdix perdix*) requires insects as chick food during the first ten weeks of rearing. Many of these insects are associated with annual dicotyledonous weeds in cereal crops in the UK. Adult partridges also feed on plants, particularly within arable crops. Management of the crop with pesticides and herbicides is therefore likely to have had a major impact on partridge populations, explaining the major decline in this bird species in the 20th century.

The impact of weed control on biodiversity within the crop has been clearly demonstrated by some researchers. Several initiatives, notably for integrated crop management, indicate there are implications for biological diversity within fields from different approaches to weed control. The protection of the farmers' investment and avoidance of risk have been the driving forces for efficient weed control in the past. However, an emerging new paradigm is to match crop production with conservation of biological resources and the development of more sustainable systems.

Weeds in crop and non-crop habitats

Typically, the term 'weed' is applied to non-crop plants in agriculture and horticulture. However, under the broader term 'vegetation management', any plants that occur in the wrong place may be regarded as weeds. Vegetation in amenity areas, aquatic systems, conservation sites, national parks, gardens and industrial sites can all include plant species that may require control or eradication.

Crop systems

Arable fields are regarded as ideally supporting only crop plants, usually as a monoculture. This ideal has guided modern weed control technology until relatively recently. Spontaneous weed communities were regarded as undesirable and weed control aimed at eradication. Thus herbicides have been developed capable of controlling a wide range of weed species, but tolerated by the crop species. The ultimate example of this is the breeding of herbicide-tolerant crops, over which broad-spectrum herbicides can be used to eradicate all plants except the crop.

However, as agriculture has developed over the past 10 000 years, so weed communities have adapted to cropping and husbandry practices. Species adapted by high seed production and with seed dormancy are now typical of arable conditions, together with a few species capable of spreading and surviving by vegetative means. A wide range of species may be found in arable and horticultural crops in Europe (Chapter 1). A phytosociological approach to weed communities has also been taken, with a range of descriptions published for the UK and elsewhere.

Grassland

Originally, pasture systems were based on indigenous grass and herb communities that were grazed and/or cut for hay for winter feeding. Fertilizer regimes allowed greater productivity and subsequently grass cultivars adapted to higher growth rates have been bred. Improved grasslands were created, based on one or a few cultivars/species, typically perennial ryegrass (*Lolium perenne*), grown as short- or medium-term leys. Under these conditions, silage cropping has become common. Weeds, whether in pasture, leys and amenity grassland, may need to be controlled; perennial weeds, such as broad-leaved dock (*Rumex obtusifolius*), may reduce pasture productivity, and annual weeds, such as chickweed (*Stellaria media*), may interfere with the establishment of sown leys.

Farmland as a mosaic of crop and non-crop habitats

Agricultural and horticultural habitats do not occur in isolation in the landscape; fields and field systems occur as mosaics of crop and non-crop habitats. The non-crop elements of agricultural land may be refuges for many plant and animal species. Whilst these elements may be regarded as sources of weed species in adjacent crops, this perception has been challenged. Some species undoubtedly disperse via seeds and propagules or vegetative spread, but most species associated with non-crop areas do not commonly pose serious threats to adjacent crops. However, these areas may be important for the conservation of biological diversity in agricultural landscapes, particularly as production methods have intensified. Studies by the Centre for Ecology and Hydrology in the UK have identified linear features in lowland agricultural landscapes as refugia for plant species diversity. These extensive studies of land use change and their ecological consequences also indicate that botanical diversity is continuing to decline in the UK. Whilst the causal effects are not agreed, they are most likely to be eutrophication and disturbance. Agricultural practices, including fertiliser and herbicide applications, are implicated.

The diversity of structure that field boundaries may have, including walls, hedges and ditches, can promote the diversity of plant communities that may occur there. The addition of conservation management in the form of permanent field margin strips or conservation headlands can further add to this diversity and protect existing habitats from some effects of adjacent farm operations. Boundaries may have a diversity of plant communities, including woodland, shrub, tall herb, grassland, wetland, aquatic and arable plant species. However, often the diversity of the margin community is low, reflecting reduced structural diversity and disturbance from fertilizer, herbicide drift and cultivation. The approaches to management promoted by several agri-environmental support schemes can enhance diversity, partly by reducing disturbance and by encouraging an increase in the area of semi-natural habitat on farms.

The perennial plant communities of the boundary may represent important refuges for species of habitats under threat in modern intensively managed landscapes. In the past, the perception that weed species spread from margins into the crop coloured the management applied by farmers. Broad-spectrum translocated herbicides were widely used, resulting in the elimination of much of the perennial herbaceous flora of field edges and promotion of a weedy ruderal flora, often dominated by barren brome (*Anisantha sterilis*) and cleavers (*Galium aparine*), both annuals adapted to germinating in shade under hedges. Under the Environmentally Sensitive Area schemes in Wales, agrochemicals are prohibited in 2 m-wide buffer zones for field boundaries. Sown margin strips also offer protection to the boundary and increase the size of perennial habitat at the field edge. Studies indicate that few perennial plant species spread successfully into adjacent regularly cultivated habitat.

Studies have also shown that the seed bank of arable fields is often impoverished, but is larger and more diverse at the field edge (Chapter 3). Within the crop habitat, there are many annual plant species adapted to regular disturbance that are now rare (see below). Prescriptions for conservation headlands and uncropped wildlife strips have been introduced to enhance the populations of these species. Clearly, permanent perennial field margin strips and prescriptions for rare arable weeds are incompatible, as the disturbance regimes for one preclude the other.

Nevertheless, in many situations it is possible to maintain a perennial margin with modified crop management alongside. The perennial vegetation can support a diverse invertebrate fauna, some associated with individual plant species, while other faunal groups, like spiders, require vegetation structure. A significant group of invertebrates overwinter in field margins and migrate into the crop in spring. Some ground beetles do the opposite, aestivating in the margin and emerging in autumn. The perennial herbaceous flora is important as cover for nesting birds, notably the grey partridge, whilst the adjacent crop habitat is vital for the insect fauna, associated with annual broad-leaved weeds, that forms chick food. Small mammals also use the perennial vegetation. Thus perennial margin strips, including beetle banks, can be compatible with conservation headlands and uncropped wildlife strips. Under the UK Countryside Stewardship Scheme, conservation headlands are promoted alongside margin strips and beetle banks, where soil types are suitable.

The perennial margin strips have a number of roles, including the reduction of spread of the few annual weeds of hedges, notably barren brome and cleavers, into the crop. Weed control may be required during the establishment of such strips. However, a sown margin can reduce the incidence of weeds at arable field edges. Grass strips also reduce the amount of fertiliser and pesticide drift reaching pre-existing boundary habitats, including watercourses, by moving tractor operations further into the field. Vegetated strips can reduce surface movement of water into watercourses, buffering fertiliser and silt burdens. However, subsurface flows are not likely to be significantly affected.

Threats to farmland biodiversity

Surveys of farmland wildlife have identified serious declines in the populations and ranges of birds, and declines in populations of mammals, insects and plants associated with arable land. Changes in arable farming practices have been identified as important factors in these declines.

Declines in farmland birds have been identified for a number of bird species characteristic of arable and mixed farmland (Table 5.1). These birds feed on seeds, invertebrates or both, sometimes at different times of year. Significant declines in the brown hare have also been recorded, associated with changes in the availability

Table 5.1 Percentage declines in the UK Common Bird Census farmland index, 1969–1994 (*Fuller* et al., *1995*)

Bird species	Decline, 1969–1994 (%)
Tree sparrow	89
Grey partridge	82
Corn bunting	80
Turtle dove	77
Lapwing	62
Skylark	58
Linnet	52

of high-quality food at certain times of year. Declines in the pipistrelle bat (*Pipistrellus pipistrellus*) are likely to have resulted in part from a lower abundance of insect prey in farmland. Information on declines in arthropods in farmland has been published for the Game Conservancy Trust's Sussex Study. In the Sussex study area between 1972 and 1990, arthropods declined by 4.2% per annum (excluding springtails and mites), with many groups of beneficial insects, such as aphid predators and gamebird food items, declining at faster rates. Bee species are particularly threatened. A range of cornfield weeds, such as corn buttercup and shepherd's-needle (Table 5.2), have declined markedly this century, to the extent that some species are now extinct in the UK. These annual flowers are dependent on the arable ecosystem, which is characterised by regular soil cultivation.

Changes in farming practices that have been identified as causing declines in biodiversity include

(1) concentration on winter crops with a consequent loss of spring crops
(2) increased farm specialisation with a decline in livestock and grass enterprises in arable areas
(3) changes in cultivation dates
(4) loss of semi-natural habitat in farmland, including field margins

The UK *Countryside Survey 1990* showed that not only had hedgerows declined in length, but the botanical diversity of many field margins had also declined through nutrient enrichment and/or herbicide drift. Data collected for *Countryside Survey 2000* indicate that hedgerows are no longer being lost, but plant species diversity continues to decline, both within fields and in the linear uncultivated features. Effects of agriculture on the environment are reported from many countries, including North America.

The role of herbicides in modifying agricultural habitats may seem self-evident. However, data for the UK are not clear. Reviews made in the 1970s and 1980s argued that herbicides facilitated winter cropping but that weed communities were largely unchanged. Nevertheless, it is clear that winter cropping results in a different weed community from that found with spring cultivations. Likewise, direct drilling employed in the 1970s was implicated in the encouragement of grass-weed populations. Thus, herbicides have effects on the population biology of weed species and on the plant community composition, by both direct and indirect means.

Impacts of farming on non-crop habitats

Plant species diversity is negatively influenced by high soil fertility, herbicide application and spray drift into the margin, high disturbance levels, decreasing landscape connectivity and reducing habitat quality.

Species diversity generally declines with increasing soil fertility. This is likely to be the indirect effect of fertility through competition rather than a direct effect.

Fast-growing species outcompete the slower-growing ones for light and nutrients. Soil fertility can be reduced by maximising the off-take, e.g. in crop yield, or by manipulation of stores and fluxes, e.g. nutrient cycling. Off-take can be increased by grazing, coppicing, burning and soil removal. These techniques are mostly used for conservation purposes. Manipulation of stores and fluxes is more controversial and may be unsuitable for conservation purposes, because nutrient leaching and erosion can be involved.

Research has found that fertilisation increased vegetation productivity significantly and tillage decreased community biomass at the start of the growing season. Disturbance increases below-ground competition and fertilisation encourages above-ground competition. It is suggested that productivity affects species diversity. Colonisation rate of perennial forbs and grasses decreased, and extinction increased, with increasing productivity of the vegetation. Accumulated litter and lower light penetration in highly productive vegetation possibly inhibit germination and survival of seedlings, thus decreasing the colonisation rate. Competitive displacement in vegetation on fertile soils increases the extinction rate, thus resulting in a loss of species diversity. The high colonisation and extinction rates of annual species are independent of productivity.

It has been shown that misapplication of fertilizer did not affect the species composition in a hedge-bottom after three years, in contrast to other studies on more natural communities. However, other studies have shown that fertilizer drift can occur, with significant effects on field-edge flora. Fertilizer did affect the growth and reproduction of barren brome (*Bromus sterilis*). Barren brome, and to a lesser extent cleavers (*Galium aparine*), responded strongly to nitrogen fertilizer, and in competition with other species. Both species grew more rapidly from seed and were more responsive to nitrogen than perennial species. However, they do need gaps in the vegetation to be able to establish. In a simulated field margin community with three monocotyledons and three dicotyledons, fertilizer and herbicide application had a significant effect on the plant community. Fertilizer application resulted in a reduced cover of white campion (*Silene latifolia*) and false oat-grass (*Arrhenatherum elatius*), and application of herbicides resulted in a decreased cover of sown grass.

A clear negative effect of fertilizer input on plant species diversity in field margins has been demonstrated, but the effect of herbicides was not so obvious after only two years. However, there is strong evidence in the literature for direct negative effects of herbicide use on arable weeds in the crop and in the adjacent margins in the USA. There were indirect negative effects on insect and bird species, mainly created by altering habitat patterns.

Non-target effects of weed control

Direct non-target effects are caused when pesticides reach situations beyond the target application area and reach species growing within the target area but not intended to be affected. The direct adverse effects of pesticides can range from outright death of a plant or population, through minor effects, to enhanced growth. The spectrum of direct effects on individuals is matched by a spectrum of indirect effects on associated fauna and flora. Direct effects on plants by pesticides can appear to be insignificant, e.g. reduced flowering. However, such impacts may be of major significance to species where seed production is the key element of the regenerative cycle of the plant. Effects on germination and early recruitment of plant species are believed to be of particular importance at a growth stage that is particularly susceptible to pesticides. Non-target effects may have subtle effects on plant community composition, mediated by plant competition or by effects on the water and chemical environment in the rhizosphere.

Indirect effects of pesticides on plants may be caused by direct effects on associated fauna, e.g. fauna that may be necessary for the plants to complete their life cycles. Pollinating insects are good examples of such fauna. Other fauna may be important for the dispersal of propagules of plant species. Dispersal, both in time (via dormant seed) and space, is a key process for the persistence of plant species in patchy habitats.

Most pesticides are used in agricultural systems, although significant amounts are also used in horticulture, forestry and non-crop situations, including amenity land. In all these situations, there may be non-target plant species growing within the target application area. Movement of pesticides to non-target areas may also occur, via droplet or vapour drift or through other secondary redistribution, e.g. soil particle movement and leaching. In agricultural situations, the nearest adjacent non-target, non-crop areas are typically field margins; these may be affected by drift.

Few reliable data are available for drift under field conditions. Recent studies have shown that under recommended spray conditions, drift to field margins is of the order of 3% of field application rates. Rates of deposition in field margins are affected by a variety of factors, including boom height, wind speed and vegetation heights. Nevertheless, higher levels of drift have been recorded on ditch banks in the Netherlands, ranging from 4 to 25%, depending on the type of spray nozzle used. Drift is normally no greater than 4% under recommended field conditions; it may occur when applications are made under less-than-ideal conditions, which may happen when spray decisions are dictated by time and management pressures.

The close proximity of the field boundary to farm operations renders them susceptible to disturbance. The addition of nitrogen and phosphorus to field margins is likely to result in dominance by responsive competitive-ruderal species and the loss of species diversity.

The drift of other agrochemicals, particularly herbicides, may also affect field margin flora. Drift does occur, though data on the impacts on flora are limited. Studies of the flora of field margins where different herbicide regimes were imposed on the adjacent arable fields have not revealed significant changes in the boundary flora. However, experimental studies on field margin communities affected by fertilizer and herbicide have shown significant impacts of fertilizer on the flora and some effects of herbicide (Fig. 5.1), dependent on the active ingredient. Detailed studies of the effects of low levels of herbicide and fertilizer on field margin communities have been made. Field experiments on a natural and a sown community were treated with a range of doses of fluroxypyr (0–50% of field rate) and fertilizer. Fertiliser contamination is likely to be a more important and more predictable factor than herbicide drift in reducing botanical diversity in adjacent non-target areas. However, drift also resulted in reduced species richness, enhancing grass biomass and reducing biomass of flower species, notably the subordinate, lower-growing ones. Most significant effects were noted with the 50% rate, but 5% and 10% doses reduced the biomass of colonising herbs and increased extinctions. The herbicide had different effects on different species. In addition to the field experiments, conventional pot experiments were made to test the effects of the different rates of herbicide on a range of the plant species, but the results did not correspond well with the field results. It was concluded that extrapolation of the results of pot experiments to normal field conditions is difficult and inappropriate.

The effects of three different herbicides (glyphosate, MCPA and mecoprop) have been tested on five field margin plant species placed in three different types

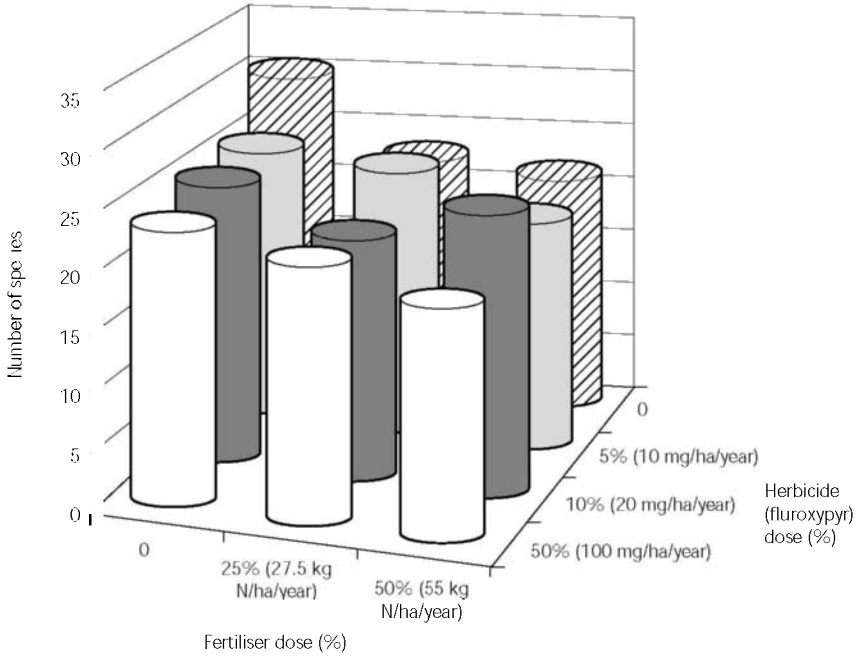

Fig. 5.1 The effects of three years of fertiliser and herbicide application (% of standard dose) on species richness (number of species/m^2) of a mixture of grassland species sown on a fallow arable field. (*After Kleijn & Snoeijing, 1997.*)

of surrounding vegetation (tall, medium and short) at different distances from the sprayer. No significant reduction in growth was recorded. However, younger plants were more affected than older ones and some species showed a response to the vegetation structure. Within 10 m of the sprayer, mecoprop drift decreased the growth of foxglove (*Digitalis purpurea*), hedge bedstraw (*Galium mollugo*), hairy St. John's-wort (*Hypericum hirsutum*), ragged-robin (*Lychnis flos-cuculi*), cowslip (*Primula veris*) and meadow buttercup (*Ranunculus acris*), and enhanced the growth of perennial rye-grass (*Lolium perenne*) and hedge woundwort (*Stachys sylvatica*).

The effects of eight different herbicides on non-target plants in field margins have been examined. They all had some damaging effect, but MCPA, 2,4-D and a coded herbicide gave more severe damage to the non-target plant species than MCPB, clopyralid, asulam, fluroxypyr and methabenzthiazuron. Other studies indicate that broad-spectrum herbicides, such as mecoprop and glyphosate, are likely to have adverse effects on field margin flora. However, examinations of field experiments where different herbicide regimes have been imposed in adjacent fields have not revealed coincident changes in field margin flora, possibly reflecting poor recovery of already impoverished plant communities.

Rare arable weeds

Many formerly common flowering cornfield weeds, such as corn buttercup (*Ranunculus arvensis*) and shepherd's-needle (*Scandix pecten-veneris*), have become rare, both in the UK and elsewhere in Europe. Recent surveys confirm the reduction in occurrence of a range of weed species in central southern England. Some species, such as thorow-wax (*Bupleurum rotundifolium*), are now probably extinct in Britain. Nevertheless, efforts to conserve a number of rare cornfield weed species are in progress. Assessments of rare weed occurrence have been made within the Botanical Society of the British Isles Scarce Plant Project and other surveys for 18 species listed in Table 5.2. Modifications to field margin management, particularly uncropped wildlife strips and conservation headlands, can allow these species to survive. Set-aside management may also provide an opportunity to encourage these annual plants in arable systems.

The timing of soil cultivation, either in autumn for winter crops or in spring for spring crops, has a marked influence on the weed communities that develop. Winter cereal crops favour autumn-germinating species, whereas spring cultivation largely eliminates these and favours spring-germinating species, such as the *Polygonaceae* (knotgrasses).

Studies of weed seed banks in arable fields show that under current management, more seed and more species are represented at the field edge than in midfield. This situation is not reported from organic arable cultivation in France, indicating that these species have the potential for occurrence throughout fields. Changing production to an organic system may allow rare weeds to persist.

Table 5.2 Rare arable flowers on UK Biodiversity Action Plan (BAP) lists, or noted under the Cereal Field Margin Habitat Biodiversity Action Plan, or surveyed under the Botanical Society of the British Isles Scarce Plant Project.

Species*	Germination†	Seedbank longevity‡	Soil type	Seed dormancy§
Pheasant's eye (*Adonis annua*) (l)	S/A		Chalk/brash	G
Ground pine (*Ajuga chamaepitys*) (l)				
Small alison (*Alyssum alyssoides*) (l)				G
Dense silky-bent (*Apera interrupta*)	A?			G
Loose silky-bent (*Apera spica-venti*)	A	1–5 y	Sand	yes
Cornflower (*Centaurea cyanus*) (m)	A/S			yes
Broad-leaved spurge (*Euphorbia platyphyllos*) (l)	A/S		Chalk/clay	G
Red-tipped cudweed (*Filago lutescens*) (m)				
Broad-leaved cudweed (*Filago pyramidata*) (m)			Chalk/sand	
Western ramping-fumitory (*Fumaria occidentalis*)			Sand/loam	G
Purple ramping-fumitory (*Fumaria purpurea*) (m)				G
Tall ramping-fumitory (*Fumaria bastardii*)	A/S			G
Dense-flowered fumitory (*Fumaria densiflora*)	S		Chalk	G
Few-flowered fumitory (*Fumaria vaillantii*)	A/S		Chalk	G
Red hemp-nettle (*Galeopsis angustifolia*) (m)	S			G
False cleavers (*Galium spurium*)				G
Corn cleavers (*Galium tricornutum*) (m)				G
Field gromwell (*Lithospermum arvense*) (l)	A–S		Chalk/clay	
Field cow-wheat (*Melampyrum arvense*) (l)	S			
Prickly poppy (*Papaver argemone*)	A/S	> 20 y		yes
Rough poppy (*Papaver hybridum*)	A/S	> 20 y	Chalk	G
Corn parsley (*Petroselinum segetum*) (l)	A		Chalk/clay	G
Purple-stem cat's-tail (*Phleum phleoides*) (l)				G
Cornfield knotgrass (*Polygonum rurivagum*)	S			G
Corn buttercup (*Ranunculus arvensis*) (l)	A		Clay	G

Contd.

Table 5.2 *Contd.*

Species*	Germination†	Seedbank longevity‡	Soil type	Seed dormancy§
Shepherd's needle (*Scandix pecten-veneris*) (m)	A/S	3–12 m	Clay	
Small-flowered catchfly (*Silene gallica*) (m)	S		Sand/gravel	
Night-flowering catchfly (*Silene noctiflora*)	S	5–20 y	All soils	yes
Spreading hedge-parsley (*Torilis arvensis*) (l)	A		Clay/loam	G
Narrow-fruited cornsalad (*Valerianella dentata* (l)	S			
Broad-fruited cornsalad (*Valerianella rimosa*) (m)			Clay-chalk	
Breckland speedwell (*Veronica praecox*)	winter			G
Fingered speedwell (*Veronica triphyllos*) (l)				G
Slender tare (*Vicia parviflora*)			Clay/brash	G

* (m) = species on BAP middle list; (l) = species on BAP long list.
† A = autumn; S = spring.
‡ m = months; y = years.
§ G = dormancy known in the genus.

Current within-field distributions in intensively managed cropping may therefore simply reflect less efficient weed control at the field edge. Therefore, in areas of intensive arable management, field margin management that allows annual cultivation, but reduces the effects of herbicides and competition from vigorous plants, should encourage these less common species.

Uncropped wildlife strips and conservation headlands, particularly where fertilizer is excluded, are the most appropriate field edge treatments for encouraging rare weeds. Uncropped strips are cultivated on an annual basis, but the arable crop is not sown and only selective weed control operations are applied. Conservation headlands were developed in Germany to conserve the rare arable flora and have been further refined for the UK by the Game Conservancy Trust to enhance grey partridge populations. No insecticides and a very limited spectrum of herbicides and fungicides are applied to the crop edge, encouraging dicotyledonous weeds and their associated invertebrates. Where rare weed species are known to occur in the crop edge, oversowing a perennial grass margin will not allow these annual plants to persist. Sown perennial grass margins are thus not recommended in such situations.

Avoiding risk to non-target areas and weeds

There are a number of approaches to reducing the risks to non-target species of weed control operations. These are based around application and product technologies, temporal methods and spatial methods and are summarised in Table 5.3.

Application methods concern the composition of the spray solution and the equipment used to apply it. Precision in delivery of herbicide to the target is essential. A great many different types of sprayers are in use (Chapter 10). A main aim of designers has been to reduce drift, both because it can result in contamination and because it represents a loss of active ingredient. Drift of droplets is a consequence of needing to cover the crop and weeds thoroughly; small droplets of solution are essential to achieve this. Other designs, such as electrostatically charged droplets, have been tried but have encountered problems in use. Air-assisted sprayers, in which the spray solution is blown downwards into the crop, may give less drift. Calibration of the sprayer, its management, and operation in the correct windspeed are all essential in reducing spray drift, as is the use of the lowest feasible boom height.

Another development which can reduce herbicide use and thereby the amount of drift, is the incorporation of mechanical weeding into control systems (Chapters 13, 14). Weeds can be managed by mechanical means, e.g. weed rakes. Alternatively, a combination of hoeing and reduced herbicide use can be successful. Between-row mechanical weeding is particularly suited to row crops, where directed sprays can achieve within-row control.

With a large number of possible chemicals to use, there is sometimes an

Table 5.3 Advantages and disadvantages of different pesticide risk management methods (after Breeze *et al.*, 1999)

Method	Advantage	Disadvantage	Comment
Application			
Sprayer design	Reduces drift	No reduction in amount applied	Manufacturers' claims may be optimistic
Active ingredient	Avoids susceptible species	Necessary information may not be available; not possible in many cases	Requires detailed information and knowledge, esp. dose–response
Adjuvant	Reduces drift; permits low doses	Conflicting information from suppliers	Simple and effective in some cases
Low-dose	Cheaper; less contamination	Less pest control	Detailed information needed
Timing			
Within season	Minimises risk; may be very effective	Difficult to achieve; few opportunities	
Between seasons	Could avoid risk	If autumn control fails then spring application essential	
Spatial			
Weed patch application	Potentially effective	Requires accurate weed mapping and precision application equipment	Under development
Buffer zones	Effective	Reduce drift; do not prevent it; use cropping land	Simple but passive methods
Windbreaks	Effective	Maintenance around field	Possibly unpredictable effects

opportunity to select one with a spectrum of activity which may be less damaging to certain types of plants than to others. Particular herbicides might be targeted more precisely to the weed spectrum present in fields. However, precise dose responses for target and non-target species are needed before this approach can be fully developed. At present, such data are not comprehensive and most herbicides have wide-spectrum activity and are not sufficiently selective.

The need to avoid contamination, as well as the economics, has resulted in the use of lower doses of many pesticides and the finding that these can often achieve adequate control. The question of the right amount of pesticide to use in a given set of circumstances has not been answered satisfactorily, because the recommended doses tend to be generally greater than are usually required, especially for weeds. There is some information on the degree of weed infestation that can be tolerated without loss of economic yield, but this, together with a robust method to calculate precise doses for a crop, would be extremely useful for risk management. Theoretical approaches indicate that this could be achieved. At present, growers have usually little more than previous experience or the recommendation of a consultant to rely upon. Not all pesticides can achieve control at low doses; on the other hand, there are some that can achieve effective control of some but not all weeds at less than half the recommended amount.

There is often an opportunity to apply pesticides later or earlier within a given season, or (particularly with herbicides) to apply in either autumn or spring. This may confer selectivity between target and non-target species. In an autumn application, a soil-incorporated pre-emergence herbicide could be used, reducing the risk of spray drift because large-droplet spray spectra can be used. The key to risk management by manipulating timing is to have a thorough understanding of the agronomy, the target and the non-target species and the precision control operations.

Precise spatial application of herbicides might be achieved by weed mapping and patch spraying, which could lead to reduced spray drift and overall pesticide use. This area is currently under development in order to improve reliability. However, probably not all species of weeds are suitable for this approach.

Separating crop from non-target organisms in non-crop areas by buffer zones is potentially effective. It has been shown that an unsprayed crop edge could reduce the drift of pesticides to ditch banks and to water to negligible amounts. Similarly, results of herbicide deposition studies showed that conservation headlands could reduce drift to field margins. The buffer technique is particularly valuable for preventing the contamination of water, although it addresses the symptoms of drift and non-target effects rather than the underlying causes. The Farmed Environment Company has investigated the development of sown margin strips as buffers in conjunction with IACR – Long Ashton in the UK. Sown buffer strips of native grasses and flowers are reasonably cheap and effective, and provide other benefits on farms, particularly enhanced biodiversity and weed control. Buffers may take up valuable cropping land, but are often placed in less productive headlands. A range of options for field margin strips are supported by the UK Countryside Stewardship Scheme that now incorporates further options developed in the Arable Stewardship Pilot Scheme. Landowners may need financial support to install these options, but advice on their creation and management is available. Where buffers also contain shrubs or tree species, biomass may provide a return for landowners. Studies of sown margin strips indicate few adverse agronomic effects and little spread of weeds into the crop.

Balancing biodiversity and crop production

From a human perspective plants can provide sources of fuel, medicines, raw materials for many processes and protection, as well as aesthetic pleasure. Crop, animal, horticultural and forestry production systems are essential for food and non-food products. These are key elements of modern land use which have evolved as agriculture and associated industries have developed. Plants are a key part of biological diversity as well. Threats to plants from non-target impacts of weed management within production systems may impact on biological diversity. Those impacts, mediated directly or indirectly through the elimination of plants or other effects, e.g. on reproductive potential, may affect ecosystem function by affecting soil processes, nutrient cycling and trophic interactions via fauna, flora, microflora and fungi.

A balance is needed between the methods of production applied, the demand for products and the environmental impacts that occur. This debate is aired increasingly within the developed world, where food shortages are largely a thing of the past. Where food is insufficient, questions of sustainability of natural production systems may seem less relevant. In the longer term, of course, self-reliance and sustainability are relevant to all production systems, particularly in the light of global effects from agriculture and forestry such as climate change.

As agricultural land use has evolved, so particular landscapes have developed. Some of the characteristic landscapes of Europe are threatened with change, as modern production methods are employed. Examples include the *montado* in Portugal and other landscapes in the Mediterranean. Even in more intensively managed north-western European landscapes, there are impacts on the environment from production, most notably for farmland bird populations and eutrophication of ground and surface waters.

Approaches to balancing these competing demands are varied, with many questions to be answered on the statutory mechanisms that may be required. For example, the role of planning authorities has been suggested as important. There is also debate on the scale of response. Should all fields be managed in a sustainable way or should different land areas be targeted for particular production systems? For example, set-aside can be used to provide positive biodiversity benefits, while intensive management continues elsewhere. Non-crop areas on the farm may also provide habitats and refuges for some species, but many plants, invertebrates and birds are dependent on and adapted to the crop area.

In practical terms, the development of integrated crop management (ICM) and integrated weed management is attempting to balance these demands. Whilst changing production to organic methods may allow rare weeds to persist, most farmers will not make such radical changes. A number of integrated production systems (Chapter 16) have been researched within the UK, the first being the LIFE project. Elsewhere in Europe, there have been a number of Integrated Farming Systems (IFS) initiatives, with the agreed principles co-ordinated by the International Organisation for Biological Control. At the core of these, the principle is to use interventions only as required, rather than prophylactic control, in order to protect crop yield within the crop rotation as a whole. The approach should be based on a sound understanding of weed and weed-seed ecology. With an understanding of crop–weed competition, farmers can deploy tillage, mechanical weed control, herbicides, the exploitation of predators and biological weed control (Chapter 17). There has been considerable interest and research into the use of weed control decision thresholds. However, practical difficulties and field-to-field variation in weed communities have limited the application of the approach. A further development is precision agriculture. In relation to weed control, there are initiatives to apply herbicides only to the areas of fields where competitive weeds occur. This will require weed detection systems and/or accurate weed mapping and possibly real-time control of the application of different herbicide products.

The core concern is the balance between adequate weed control, including the prevention of weed-seed build-up, and the requirement for some plants to support biological diversity within crops. For some, clean crops and zero tolerance of weeds constitute the approach, with non-crop areas supporting biodiversity. This may be suitable for large countries, such as the USA. However, in western Europe, where the landscape is almost entirely agricultural, different approaches are required. These should be based on integrated weed management, though modifications to crop management in selected areas of fields, such as conservation headlands and uncropped wildlife strips, may provide sufficient resources to maintain biological diversity of the farmed environment. Further studies at the appropriate spatial scales for different flora and fauna are required, in order to suggest appropriate practical modifications to farm management.

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Chapter 6
Herbicide Discovery

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Introduction

Vast amounts of money are spent each year by agrochemical companies who strive to discover new and commercially significant crop protection agents. The cost of launching a new product is very high and has been reported to vary from as little as \$40 million to as much as \$150 million. Without a doubt, both of these figures contain some truth but a figure on the total spent each year on research and development can be estimated by assuming that the 'average' company spends about 9% of sales on R&D investment and in 2000 agrochemical sales were over \$30 000 million. This gives a figure of \$2700 million spent by the industry on R&D in a single year. This is clearly an overestimate as about 50% of today's agrochemicals are manufactured by generic companies with little or no research capacity and hence no R&D expenditure, but it does make a point about the costs of discovery.

Again, the time needed to take a compound from synthesis to launch is variously reported. It is not unusual for a new herbicide to take ten years from initial discovery of biological activity to commercial launch. With a patent life of only 20 years and the need to file a patent as early as is reasonable to ensure compound protection, the time left to recoup the investment in a new product is alarmingly short. This means that agrochemical companies must concentrate on existing large markets where it is well known that products will be used and where a small share of the market will provide sales that will repay the initial investment.

This can be demonstrated by a simple example. If a new herbicide is developed at the overall cost of \$75 million and it can be expected to have a viable commercial life of ten years, it must make a profit of at least \$7.5 million each year, more if there is to be any real income associated with the discovery that can be invested into the future research and development of the company. It is unusual for a new introduction to achieve more than a 10% share of a market and so the new product has to be sold into a market that is well over \$100 million a year. This means that a new herbicide must be targeted at small-grain cereals (particularly wheat), maize, soybean or rice, or at the total, non-residual herbicide market.

Commercial targets

The typical, commercially viable product is based upon the size of the global market and the opportunities that exist within each market for the introduction of new products. This means that the key markets for herbicides are selective control of weeds (broad-leaf, grass and sedge; annual and perennial) in maize (corn), soybean, rice and small-grain cereals. Knockdown (and preferably some residual) activity against all weeds in plantation crops and non-crop land is another important market. This market is becoming increasingly important as molecular biology introduces more and more crops that possess tolerance to currently available non-selective herbicides. Key amongst these are RoundupReady and LibertyLink crops although bromoxynil-tolerant cotton, sethoxydim-tolerant maize and acetolactate synthase (ALS)-herbicide-tolerant crops are also establishing market share. Indeed, it is suggested that some agrochemical companies, having discovered a totally non-selective herbicide, have delayed its launch until a tolerance gene has been identified that would markedly increase the potential market for the compound.

In all crops, the key word is 'selective' and this means that the herbicide is not only selective within the crop but also non-toxic to other, non-target species, as well as having a benign environmental profile. Systemicity is a desirable trait, as is a novel mode of action; compatibility with existing crop protection products and agricultural systems is essential.

In the field of herbicide discovery it was once thought that selectivity was the real target, because all weeds can be controlled by mixtures of herbicides. This still cannot be done selectively in all crops for all weeds. Selectivity has been improved by seeking herbicide safeners, which improve an inherent selectivity that a crop possesses for an active herbicide. There are several combination products on the market today.

Source of chemicals

The complex process of discovering novel, biologically active compounds that have any potential as new-product candidates is dependent upon the interaction of many different people with different skills and different approaches to discovery research. Each one has a significant role to play and it is essential that they all work together for the overall good of the project rather than to ensure that their input is recognised over others. In the first part of this process the key players are synthesis chemists working closely with physical chemists, and biologists working with the support of biochemists. Increasingly, there is an involvement with molecular biologists who use knowledge of genome sequences to identify new biochemical target sites. Once a new target site is identified, it must be incorporated into an *in vitro* screen so that a large number of compounds can be tested against it.

It is often said that compounds for evaluation in biological screens can come from a variety of different sources. Empirical screening demands compounds from sources that have little or no connection with recognised biological activity. These are compounds that are synthesised or purchased because they *can* be made or *are* available for purchase. It used to be argued that most agrochemicals were discovered in this way; examples of successful products include trifluralin and paraquat. In recent years, the pharmaceutical industry has introduced rapid synthesis techniques as a means of supplying large numbers of compounds to its rapid high-throughput screening systems. Most pharmaceutical screens are assays *in vitro* on identified target enzymes which are always rapid to run and require only small quantities of chemical. It is becoming possible to screen hundreds of thousands of compounds each year in any test, but it is difficult to find so many new compounds for screening. Combinatorial chemical approaches are now being applied to the production of new compounds in both the agrochemical and pharmaceutical industries. The approach is simple in principle and can be demonstrated with the following example. Standard chemical reactions are used to assemble selected sets of building blocks into a huge variety of larger structures. Suppose there are four molecules, A1, A2, B1 and B2, such that A1 and A2 are related, as are B1 and B2, and these two different classes of chemical can react together to form new molecules. Combinatorial chemistry allows the rapid synthesis of all possible combinations of analogues: A1–B1, A1–B2, A2–B1 and A2–B2. As more variations in A and B are employed, more compounds that are members of the same library can be made. These compounds can then be further modified by the introduction of another series of molecules (C1, C2 etc.) with which the combination products can react to produce molecules such as A1–B1–C1, A1–B2–C1, A1–B3–C1 and so on. Many techniques are available for separating or identifying the different chemicals. More information on the preparation of such chemical libraries has become available since 1995. It must be remembered, however, that the separation of compounds is important in order to identify the most active member of a chemical series and it is always easier for a chemist to separate insoluble compounds than those that are soluble. Unfortunately, the physicochemical properties that allow for easy compound separation are not those that are found in biologically active molecules, so the originating chemist must compromise between ease of purification and likelihood of biological effect. It is essential that synthesis chemists concentrate primarily on 'biophilic' compounds for screening programmes.

The most successful method of producing new products is through copying the successes of others – 'me-too' chemistry. The success of competitors is usually indicated by classical 'me-too' synthesis of compounds just outside their patent claims, but it should also be remembered that additional synthesis around your own active leads and products will often be very successful. There are a great many examples of successful synthesis in this area, including Du Pont's own new sulfonylureas derived from the original products such as chlorsulfuron and the sulfonylureas of competitors such as Novartis, AgrEvo and Takeda. In addition, there are examples of synthesis based upon sulfonylurea chemistry which led to the discovery of compounds with the same mode of action but that had different selectivities and different chemistry, such as the triazolopyrimidine sulfonanilides from Dow.

Natural products have supplied a great number of active molecules and ideas for actives, although the opportunities in herbicide discovery are limited. Classical fermentation has produced bilanafos, but this product cannot compete economically with the synthetic compound glufosinate. However, the producing organism, *Streptomyces hygroscopicus*, has been found to contain a gene coding for an enzyme that acetylates the active acid, rendering it non-phytotoxic. This phosphinothricin acetyl transferase gene (*pat*) has been isolated and used in truncated form to transform crops such as maize to render them tolerant of over-the-top applications of the herbicide glufosinate-ammonium (Liberty). It is claimed that some ideas for herbicides were derived from higher plant natural product chemistry; key amongst these are the triketones from Syngenta, and BASF's cinmethylin.

Biorational synthesis was the dream of yesterday's biochemists – identify an enzyme that is essential for the survival of a target weed, design an inhibitor of this enzyme and wait for the weed to die. To date there are no commercial examples of compounds resulting from this strategy. However, the application of structural and functional genomics allows key enzymes from target organisms to be identified very easily and the relevance of these enzymes to the target's normal function can be determined. It is relatively easy, using antisense technology, to confirm that a predicted target site is essential for growth and that interference with the gene product (usually an enzyme) is lethal. If the target organism dies, the enzyme is essential and screening for inhibitors can be justified.

Over 50% of commercial herbicides inhibit just three biochemical targets and the total number of targets is relatively small (Table 6.1). Clearly, a new mode of action for a new herbicide product would give that compound an advantage over existing products. Huge progress has been made in the field of genomics over the last five years and the complete genome of *Arabidopsis* is all but complete. This knowledge will identify approximately 25 000 genes and it has been suggested that there may be as many as 2000 genes that are essential for plant growth. Once a new gene product has been identified as essential for plant growth and it has been confirmed that the gene is plant-specific (and hence its inhibition will have no effects on non-target organisms or man) it is relatively easy to clone the gene and over-express it in a producer organism to supply enzyme for use in a high-throughput screen *in vitro*.

Biological screens

A good screen *in vivo* demands that as little time as possible is spent testing compounds that are not good enough to justify further evaluation, but must also

Table 6.1 The modes of action of commercial herbicides

Target	Number of herbicides
Photosystem II	59
Acetolactate synthase	43
Protoporphyrinogen IX oxidase	28 (−3)
Auxin mimics	20
Acetyl CoA carboxylase	16
Non-specific chloroacetamide target	15
Cell division	14
Phytoene desaturase	11
Hydroxyphenylpyruvate dioxygenase	3 (+3)
Oxidative phosphorylation	3
Cellulose biosynthesis	2
Photosystem I	2
Auxin transport	1
Enolpyruvylshikimate phosphate synthase	1
Dihydropteroate synthetase	1
Glutamine synthetase	1
Lycopene cyclase	1
Unknown (or not stated)	48
Total	272

From: D Cole *et al.* (2000).

ensure that no compound that is a potential lead for further synthesis effort is rejected prematurely. However, it must also be remembered that the search for biological activity is termed ‘screening’ and it is the number of compounds that pass each stage of the screen that determines how much time, and more importantly money, are spent on each phase and how much are wasted on compounds of no biological interest. Consequently, screens *in vivo* must test compounds at rates that will ensure that nothing with activity is lost; however, such a strategy demands relatively large amounts of the chemical. Once activity has been confirmed, subsequent evaluation is based on the level and spectrum of activity in comparison with standards of known biological efficacy – both internal standards whose chemistry is related to the novel compound under test, and external standards that have a similar spectrum and mode of action.

Traditional screening

Regardless of the source of the compounds, it is important to establish cost-effective, efficient and reliable biological tests (screens) to determine whether they have any useful herbicidal activity. A good screen is one that picks up all useful biological activity, not one that identifies all biologically active compounds. Time spent determining whether or not activity is good enough is often time wasted.

Typically a screen used to be designed as a low-throughput, high-rate test where it was hoped that all actives were found (Table 6.2).

In this type of assay system, if the *in vitro* screen was there at all it was used to add additional information to the *in vivo* data. The spraying of plants necessitated use of relatively large quantities of compound, commonly as much as 750 mg. Increasingly *in vivo* screens are being miniaturised to reduce the amount of compound that is needed and to allow for higher compound throughput. It is not unusual to run *in vivo* screens that require 10 mg of chemical or less, rather than the hundreds of milligrams needed previously, and to evaluate several hundred thousand compounds each year.

Combinatorial chemistry, because it produces libraries of compounds in very small quantities, has led to the introduction of *in vitro* assays based on known modes of action or on novel modes of action derived from genome-based target identification tests. These *in vitro* assays will only find compounds that are active against the particular target that is being used in the assay whilst, in a whole-organism test, an effect will be produced with any compound that interferes with any lethal site of action. *In vitro* assays use very little chemical and can be used to evaluate many millions of compounds each year. In addition, the shape of the binding site of the target enzyme can be determined by comparing the three-

Table 6.2 Typical low-throughput *in vivo* screen

Screen	Rate	Decision
In vivo		
Primary	High dose, indicator species	Reject inactives
Secondary	Dose response, indicator species, standards	Select compounds with useful biological effects
Tertiary	Low dose, timing of application, formulation effects, volatility studies, volume, increased number of target pests/diseases/weeds and crop selectivity, mode of action studies	Select compound for field testing, identify crops and targets, define preferred formulations
Field evaluation	Range of rates to give information on dose that fails to control, several formulations, in several countries	Select compounds for development
In vitro		
Primary	Look for effects on target enzyme that are specific to that enzyme	Select compounds for synthesis effort and for *in vivo* assays

dimensional structure of compounds that are inhibitory, allowing even better inhibitors to be designed and synthesised.

Natural products are another source of new compounds that demand special treatment. The time the chemist spends synthesising a compound is always the main cost associated with its testing, but with a natural product, the costly part is the analysis of the fermentation broth or organism extract and the determination that the activity is due to a compound that is novel. In addition, the isolation and characterisation of the active compound involve a great deal of time and therefore cost. Screening natural products is more like screening mixtures, with the proviso that there is no indication of how many compounds are present, the quantity of each one in the sample, whether they are related and whether there is a positive or negative interaction of two or more components within the sample. Once activity has been discovered, separation and re-testing are essential.

High-throughput screening

If the quantity of compound available is very small, the type of test that can be conducted on that compound is limited. It is always important when setting up and running an assay that the questions that are being asked are clearly identified and interpreted. An old-style, high-dose *in vivo* screen is designed to reject inactives and do nothing else. It must ensure that a compound that possesses no useful biological activity goes no further. A site-specific *in vitro* assay must give an indication of the level of inhibition of the target enzyme and ensure that it is not a general biocide. The determination of whether or not that compound has biological effects when applied to a plant is not the purpose of the screen; the primary result is an indication of an effect at a specific enzyme, and this will provide information to the synthesis chemists and biochemists that will advance the development of site-directed enzyme inhibitors. Making the compounds work following spray application is a different problem that requires a different test.

These assays are good at identifying the most active enzyme inhibitor but they do not show that such compounds are active on the whole plant. For this reason, it is essential that assays are run *in vivo* before more work is done on the compounds.

Interactions between disciplines

It is true that an agrochemical becomes a successful product because of the biological effect that it offers the farmer. Farmers do not buy the tris(2-hydroxyethyl)ammonium salt of 2,4-dichlorophenoxyacetic acid as such; they buy cost-effective broad-leaved weed control in cereals. Hence, it is biological effect and commercial advantage that determine whether a compound launch will be successful. In today's agricultural world, there are a great many excellent products but more compounds continue to be launched. As new products with lower rates of use, increased weed spectrum, reduced impact on the environment and improved crop selectivity reach the market, the hurdles that have to be overcome by a development candidate also increase. Hence, it is important that members of the discovery team work closely together to optimise the activity once discovered.

In a biological screen designed to find compounds with a specific biochemical effect, it is important that the biochemical target is shown to be essential to the target pest and, if possible, specific to the pest. Such an assay will give the developing company a commercial advantage while it remains company-confidential. However, once the compound is launched, competitors can determine this new mode of action and establish screens that exploit it. An example was the launch of sulcotrione by Zeneca (now Syngenta). Sulcotrione was the first commercial herbicide that inhibited the enzyme *p*-hydroxyphenylpyruvate dioxygenase, a key enzyme in plastoquinone biosynthesis in plants. Rhône–Poulenc (now Aventis) exploited this discovery and launched their own inhibitor, isoxaflutole, based on structure–activity studies – different chemistry, new patent, identical mode of action.

Other aspects of biochemical input into product discovery can be realised through asking questions, e.g. on the basis of selectivity in different crops. If a herbicide were required that was selective in a crop such as maize (corn), an examination of the structures of compounds that showed this selectivity together with a determination of the biochemical basis of the selectivity would allow compounds to be synthesised that could be used selectively in maize. Typically herbicides with maize selectivity are those that contain elements that can conjugate with glutathione (epoxides, halogens, sulfoxides), that can be *N*-dealkylated or that can be hydroxylated by the non-enzymic interaction with benoxazinone. If such characteristics can be built into a development herbicide candidate while retaining its effect on the targeted enzyme, then the result will be a maize-selective herbicide. A similar exercise can be carried out with other targets and with other biological effects but successful application of these strategies demands collaboration between biologist, biochemist and ultimately, of course, synthesis chemist.

Physicochemical characteristics are important in terms of movement to the target site, persistence in the field and in the target organism, volatility, soil persistence and mobility, and photostability. It is possible to determine which compounds are likely to cause potential problems in effectiveness or in terms of environmental pollution before they are made. This is the input from the physical chemist. There is a story, that may be anecdotal, of a chemist who had synthesised a compound that was ten times more effective at inhibiting non-cyclic photophosphorylation than diuron; it was active at nanomolar concentrations. However, when sprayed onto plants it was completely ineffective. The disbelieving synthesis chemist would not accept that a compound this active in an assay *in vitro* could be without effects *in vivo*. Discussions with a physical chemist would have helped point out that a compound with a log P (partition coefficient, reflecting the relative solubility in water and in fats) of more than 8 would not have entered the plant, let alone the chloroplast where the binding site was located. This was a typical case where the absolute biological effect was not the key factor – ensuring that it arrived at the target was much more important than absolute activity, and a compound one hundred times less effective at the binding site but with a log *P* of 2–3 would be the preferred candidate.

Volatility is also an important attribute of an agrochemical. Volatility can be both a useful property (as it allows redistribution within the crop) or a problem as in the case of herbicide drift, e.g. for many amines of 2,4-D. It is now possible to determine, within an order of magnitude, the volatility of a compound before it is synthesised. This level of accuracy permits those compounds that will be too volatile to be discarded before they progress to manufacture. Similar reasoning can be applied to candidate compounds in terms of photostability and of persistence in groundwater and elsewhere in the environment.

If a compound is to become commercially successful it must be formulated in a way that allows it to be applied in the field. Early-stage screening *in vivo* is always undertaken with simple preparations that allow the compound to be applied and that maximise the cover and penetration. It is usual to dissolve the compound in a solvent that is miscible with water, such as acetone, in combination with a biologically inert surfactant and then to apply the compound dispersed in a water carrier. Gone are the days of pre-formulating new compounds in commercial-type systems, and it is common with the high-throughput screening of today that preparation and application be automated. The less time is spent selecting the compounds that demand additional examination, the more is the time that can be spent testing compounds in a variety of formulation types, often dependent upon the crop to be treated and the pest to be targeted.

Modes of action

Table 6.1 (above) shows that the biochemical modes of action of today's herbicides are restricted to only a few targets. For this reason it is important to seek new targets to give newly introduced herbicides a potential commercial advantage over those already in the market place. But it is also important to ensure that activity against a known and therefore proven target is not missed. The key modes of action of current commercial herbicides are described below.

Photosynthesis inhibitors

Photosynthesis involves the conversion of light energy into chemical energy (the light reaction) and the incorporation of carbon dioxide into sugars (the dark reaction). The light reaction captures light energy and converts this into chemical energy through the electron transport chain. The products of the light reaction are chemical energy in the form of ATP, reducing power in the form of NAPDH and oxygen as a by-product. The light reaction is divided into two cycles: photosystem I or cyclic photophosphorylation; and photosystem II or non-cyclic photophosphorylation. Both involve the capture of light energy by chlorophyll, a photoreceptor, and the acceptance of electrons from the splitting of water. The capture of these electrons increases the energy level of the chlorophyll to the so-called 'singlet' state and this then returns to the ground state as the electrons flow through an electron transfer chain to produce ATP and NADPH. If the electron transport chain in non-cyclic photophosphorylation is interrupted and light continues to fall on the chloroplast, the energy level of the chlorophyll is raised from the singlet state to the triplet state. Triplet chlorophyll can interact in a damaging way with membrane lipids but, more importantly, it can excite oxygen, there in abundance because of active photosynthesis, to a singlet state. This singlet oxygen is very reactive and it interacts with cellular lipids, proteins, nucleic acids and many other plant cell components, thereby inducing cellular disorganisation and plant death. Many early herbicides, including the 1,3,5-triazines, phenylureas and uracils, inhibit non-cyclic photophosphorylation and it is still a major target for herbicides although it is rare for new compounds to have this mode of action.

Cyclic photophosphorylation is also a highly energetic reaction. The bipyridiniums, paraquat and diquat, divert the electron flow of cyclic photophosphorylation (photosystem I). The capture of an electron from the chloroplast reduces the herbicide and the reduced herbicide reacts with oxygen to form superoxide. Superoxide produces hydrogen peroxide within the chloroplast and these two compounds interact to form hydroxyl radicals in the presence of an iron catalyst. Hydroxyl radicals are very damaging, leading to the destruction of the cellular components and hence to rapid plant death.

There are a number of other herbicides that affect photosynthesis indirectly. Pyrazole herbicides such as benzofenap, pyrazolynate and pyrazoxyfen interfere with chlorophyll biosynthesis and have found commercial application for the control of annual and perennial weeds in paddy rice and maize. The enzyme *p*-hydroxyphenylpyruvate dioxygenase is involved in the conversion of *p*-hydroxyphenyl pyruvate to homogentisate, a key step in plastoquinone biosynthesis. Inhibition of this enzyme has an indirect effect on carotenoid biosynthesis as plastoquinone is a cofactor of the enzyme phytoene desaturase. The new maize herbicide, isoxaflutole, and the triketones inhibit *p*-hydroxyphenylpyruvate dioxygenase and this leads to the onset of bleaching in susceptible weeds and ultimately to plant death.

In addition to the green chlorophyll pigments in leaf chloroplasts, there are other pigments that can also capture light energy but that also protect the leaf from damaging radicals by quenching them. Carotenoids are examples of this type of pigment. The inhibition of carotenoid biosynthesis removes these protective pigments from the chloroplasts and leads to damaging effects within them. Herbicides that have been shown to interfere with carotenoid biosynthesis include norfluazon, fluridone and diflufenican. These compounds interfere with the desaturase enzymes that convert phytoene to lycopene, whereas amitrole prevents the cyclisation of lycopene to form the carotenes.

There are several products that exert their effect through the accumulation of abnormally high levels of chlorophyll precursors. A structurally diverse range of herbicides has been shown to inhibit protoporphyrinogen oxidase, a pivotal enzyme at the branching point of the porphyrin pathway leading to both haem and chlorophyll biosynthesis. The inhibitors of this process can be classified into three major chemical groups: the nitrodiphenyl ethers (acifluorfen, lactofen), the phenyl heterocycles (oxadiazon and sulfentrazone) and the heterocyclic phenylimides (flumiclorac).

These compounds exert their effect through inhibition of membrane-bound chloroplastic protoporphyrinogen oxidase, leading to a transient accumulation of protoporphyrinogen IX. This leaks out into the cytoplasm, where it is converted into protoporphyrin IX by the herbicide-insensitive plasma membrane protoporphyrinogen oxidase. The protoporphyrin IX reaches very high levels in or near the plasma membrane and, being a photodynamic pigment, generates highly reactive oxygen radicals in the cytosol. The plasma membrane is therefore rapidly destroyed, leading to cell death. This mode of action has been shown to be very effective for two good reasons. There is little substrate competition with the herbicide because the substrate is lost to the cytoplasm when inhibition occurs and protoporphyrin IX will accumulate even when only a small proportion of the chloroplast protoporphyrinogen oxidase is inhibited.

Amino acid biosynthesis inhibitors

Unlike animals, plants have to synthesise everything that they need for efficient growth. Photosynthesis is one fundamental biosynthetic process but plants also synthesise other components that animals do not. These biosynthetic processes are good examples of potentially plant-selective herbicidal targets. As amino acids are the building blocks of proteins, their biosynthesis is one such process.

Aromatic amino acid biosynthesis inhibitors

The shikimate pathway is the biosynthetic route to the aromatic amino acids tryptophan, tyrosine and phenylalanine as well as to a large number of secondary metabolites such as flavonoids, anthocyanins, auxins and alkaloids. One enzyme in this pathway, enolpyruvyl shikimate-3-phosphate synthase (EPSP synthase), is inhibited by the herbicide glyphosate.

Branched-chain amino acid biosynthesis inhibitors

The branched-chain amino acids, leucine, isoleucine and valine, are produced by similar biosynthetic pathways. In one pathway, acetolactate is produced from pyruvate and in the other acetohydroxybutyrate is produced from threonine. Both reactions are catalysed by the same enzyme, which is known as both acetolactate synthase (ALS) and acetohydroxy acid synthase (AHAS). This enzyme is the target for a number of very active, low-dose herbicides, including the sulfonylureas, imidazolinones, triazolopyrimidine sulfonanilides and pyrimidinyl-oxybenzoic acid analogues.

Glutamine synthetase inhibitors

The enzyme glutamine synthetase is very important in the control of nitrogen metabolism in plants. It catalyses the combination of ammonia with glutamate to form glutamine. Glutamine is key in the transamination of keto acids in the synthesis of several amino acids and also provides an effective method of maintaining a low level of ammonia within the plant's cells. This enzyme is competitively inhibited by the transition state analogue, glufosinate.

Auxin-type herbicides

Compounds that control the growth and differentiation of plants are well known and compounds that interfere with the function or that mimic the effects of such plant growth regulators would be expected to be effective as herbicides. Indole-acetic acid is a plant growth regulator whose concentration in the plant is carefully regulated by synthesis, conjugation and degradation. Auxin or hormone herbicides have been available to the farmer for over 40 years, the first compounds being 2,4-D and MCPA, and a wide range of compounds with modes of action that are thought to be the same as the aryloxyalkanoic acids have been introduced since 1945. Notable amongst these are the benzoic acids (dicamba) and the pyridinecarboxylic acids (clopyralid). Although the symptoms produced by all these compounds are similar (stem enlargement, callus growth, epinasty, leaf deformities and the formation of secondary roots), the absolute mode of action has yet to be confirmed. It is thought that the compounds act as auxins, binding to the auxin receptor in the sensitive weed, and that they continue to exert their effects because the plant is unable to lower their concentration.

Lipid biosynthesis inhibitors

Lipids are essential plant components as they are constituents of membranes and cuticular waxes as well as being major seed storage products. The fatty acid constituents of lipids are synthesised from acetyl coenzyme A under the influence of the enzyme acetyl coenzyme A carboxylase (ACCase). Two groups of herbicides inhibit the action of ACCase, the aryloxyphenoxypropionates and the cyclohexanedione oximes. Another phytotoxic effect is the inhibition of the conversion of fatty acids into very long-chain fatty acids, a process that is specifically inhibited by the thiocarbamate herbicides such as EPTC and triallate.

Cell division inhibitors

Cell division is a fundamental prerequisite for plant growth. The meristematic regions of the plant are the targets of two major groups of herbicide that interfere with the organisation of the microtubules that are essential for the formation of the mitotic spindle along which the chromosomes separate during mitotic cell division. The microtubules are composed of both α-tubulin and β-tubulin that are brought together at the microtubule organisation centre to produce the microtubules themselves. The 2,6-dinitroanilines (trifluralin) interfere with the formation of the tubulins directly, whilst the carbamates prevent the organisation of the microtubule organisation centre itself. The result of this disruption is a failure of the cell division process, and plant death.

The 2-chloroacetanilides are also suggested to inhibit cell division in susceptible weeds, and it is likely that they alkylate the sulfydryl groups of certain essential plant enzymes. The rice herbicides cinmethylin, mefenacet, daimuron and methyldymron also interfere with meristematic activity in susceptible species.

Inhibitors of cell elongation

The *N*-arylalanine ester herbicides such as benzoylprop-ethyl, flamprop-isopropyl and difenzoquat prevent cell elongation in certain grass weeds, allowing the crop to overtop them. The weeds are thus out-competed and die. The exact mode of action is not certain but it is proposed that these compounds interfere with the site of action of the auxins.

Miscellaneous

The herbicide dichlobenil is believed to exert its effect through the inhibition of cellulose biosynthesis of actively growing plant tissue, leading to a cessation of cell division, and death.

There are a number of herbicides whose mode of action is not known or uncertain. These include compounds such as the organophosphorus herbicides anilofos, bensulide, butamifos, fosamine and piperophos and the benzofuranyl alkanesulfonates benfuresate and ethofumesate.

Filing a patent

It is essential for any organisation that is research-based to be given protection for its inventions so that it can reinvest any profit from the commercialisation of its invention in further innovative discovery. Patent legislation was introduced to ensure that this was the case. In the past, each individual country developed its own patent law and, although these laws are broadly similar, each country has its own interpretation of what can be covered in a patent application, how wide each claim within a patent can be, and what represents patent infringement. It is therefore not possible in this chapter to establish the procedures for filing patents in each of the countries. Nevertheless, there is a strong tendency for countries to conform in their patent laws through international treaties – starting with the Paris Union of 1883.

The unification of patent law has continued, with progress in Europe through the establishment of the European Patent Office. The European Patent Convention (EPC) allows a single patent application to be recognised in up to all 14 of the countries that are signatories. The Patent Co-operation Treaty (PCT) is run by the World Intellectual Property Organisation (WIPO) and allows a single patent application to be covered in up to 45 member countries.

The General Agreement on Tariffs and Trade (GATT) Trade Related Aspects of Industrial Property (TRIPS) has increased the movement towards unification of the control of intellectual property and the granting of licences. It is envisaged that the movement towards the global unification of patent legislation will continue, albeit at a very slow rate.

It must always be remembered that the granting of a patent gives the inventor the right to stop others exploiting that invention commercially for a period that is usually 20 years. It does not give the inventor the right of use. There are many possible reasons why the inventor may be prevented from exploiting his or her invention. It may be too expensive to make, impractical, unsafe or an improvement over an existing patent whose owner is unwilling to license the new inventor, or there may be no customers.

Novelty

Above all, an invention must be novel. If there are prior publications, the invention is not new. Publications are considered to be both the scientific literature and patents; in addition, mention in a lecture or in an e-mail is included in this definition. If the invention has been used publicly, even in secret, then it is not considered novel. In patent law terminology the invention must not be part of 'the common general knowledge'.

Invention

There must be an inventive step in a patent application. It is argued that any discovery that is an obvious next step to anyone 'skilled in the art' is not an invention. It is not possible to patent a 'mere discovery' such as gravity, because there is no invention in discovering something that exists. To be inventive it must not be obvious to someone 'expert in the art'. Hence, a patent application that has been derived from a known or predictable effect will suffer from the possibility of attack on the grounds of obviousness.

Sufficiency

In order to guarantee the widest possible patent and, thereby, the widest protection of an invention, it is valuable to include as many different substituents as possible within the general chemical formula, both when filing a provisional application and when completing that application. However, the EPO has decided that 'functional terms' (terms that describe a particular type of chemical substituent) can be used but these must be precise and clear. The claim of 'substituted alkyl', for example, may not be acceptable but 'C–1 to C–4 substituted alkyl' might be. When defending the scope of their claim, patent applicants often state that the patent is a 'pioneer patent claim', i.e. the first in a new area of chemistry. In these cases, more general claims for chemical substituents can be made than would normally be accepted. However, such claims often expose the inventor to challenge by competitors, a challenge that may be won but resolution is usually protracted and expensive. In terms of biological effect and use, a simple claim for all solutions to an identified problem without technical details to achieve these solutions is always non-allowable.

Utility

In patent law it is essential that a patent application must include claims for the use or utility of the invention. It is not sufficient to claim that a discovery is novel if it has no use. Within the agrochemical business, a new chemical will only be worth the expense of patenting if it has a valuable biological effect – a use. In molecular biology, the patenting of genes is affected by this need for utility in that it is not enough to isolate and sequence a gene and then file a patent application on it, as there is no identified use for the 'invention'.

Enabling disclosure

A patent, once granted, allows a monopoly to the inventor for a period of 20 years. In return, the inventor teaches the general public something that was not known before. It is essential, therefore, that the patent application provides enough information for those 'skilled in the art' to repeat the experiment – or reduce it to practice.

Ownership

The body or individual applying for a patent must be the owner of that invention for the granting of the patent to be valid.

Where to file

Assuming that these requirements are met, the next decision is in which countries to file. It is clear that a new herbicide (indeed any agrochemical) that is effective in any crop must be protected from exploitation by competitors in the countries in which that crop is a major component and, hence, where a major market exists. However, if a patent is filed only in countries where the crop is grown, the compound can still be manufactured legally in nations that do not have a major area growing the crop but that possess major manufacturing expertise. It is true that these countries cannot sell into the major markets that are protected, but they can sell into other countries where patent law is not so comprehensive and, of course, into countries where no patent is filed. Hence, choice of countries is a key decision in filing patents.

When to file

Once it has been decided that a discovery is sufficiently valuable to justify the expense associated with patent applications, the question arises of when the patent should be filed. If an application is made too early, the company may find that it has little substance within the claim and that its patent is of little value. Also, the earlier a patent application is filed, the earlier it loses patent protection. If a patent is filed too late, there is always the possibility that other organisations may have already filed a conflicting patent or that the work may be published by a competitor or by an academic.

This situation is complicated by the fact that the applicant is only entitled to the priority filing date if the patent application is completed within 12 months of this original filing by additional data or examples. However, most organisations working on new chemistry that is sufficiently novel to justify the filing of a patent application do not cease synthesis as soon as an application is filed, nor do they continue to work within the relatively narrow confines of the general formula that constitutes the new compound claim. Any biologically active chemistry that can be related to the chemistry of the original filing but is not protected by the new chemistry claim can be added in the form of an additional patent within the 12-month period allowed for patent completion. Any subsequent patents retain as their priority date the date at which they were filed, but can be pulled together into a single completed patent when the original application is completed. This is known as cognating the related claims. However, the date of each component of the invention will remain the date at which the additional claim was added.

What do you claim

When the particular timing for filing a patent application has been decided, the next decision that has to be made is what will be claimed within the application. Do you claim a specific compound or group of compounds; a process for manufacture; a use; a formulation; a mixture of your product with others; all intermediates? The relative merits of these alternative strategies are discussed below.

New substance generic patents

The most valuable type of patent is one that claims the chemistry of a new class of compounds with an identifiable and 'useful' biological effect or use. In most countries it gives the inventor ownership of those compounds for a period of 20 years from filing. Such a patent is often referred to as the dominant patent, in that it covers the product in any form, however it is made or used.

It is usual for a new chemistry patent application to include broad claims for a general formula with narrower specific species subclaims. These subclaims usually, but not always, identify the compound of choice, a method for its production, its formulation and its mixture with other compounds. It is generally true that any new compound claim must include all known uses of the compounds that are claimed. It is important, however, to ensure that any subclaim does not restrict future opportunities for subsequent claims by the inventor.

If there is a dispute about the first to discover a patent, the Patent Office has the right to investigate all laboratory notes and other information relating to the discovery – often a disruptive and time-consuming process. For this reason, it is important that discovery groups ensure that laboratory books are completed each day, dated, countersigned and authenticated. Each page has to be completed and loose-leaf books are not acceptable.

The approach of filing patents on 'pro-pesticides' is one that is often challenged as lacking in novelty if it is not possible to challenge on the basis of infringement. For instance, in the case of alkanoic acid herbicides, it has been shown that the hydrolysis of esters to the parent acid is the toxifying process. The acid is the herbicide and the ester formulation is merely a different way of presenting this herbicidal acid to the target weeds. Hence, all esters are obvious. But if a particular ester gives the herbicide unexpected properties, be it in terms of water solubility, volatility, penetration into the target plant, stability within the crop or other useful biological effect, is this an *obvious* extension of the herbicidal acid?

Process patents

It is essential for a new compound claim patent to include a method of synthesis of examples within the application; often there is also an indication of a manufacturing process that could be used in the production of the compound of choice. This method of synthesis has to be the best one known to the inventor at the time, such that someone 'expert in the field' could repeat the experiment and test the discovery. If the patent is a dominant patent, as it usually is, there is no disadvantage in revealing a process within a patent application as a competitor is not able to exploit the discovery without the applicant's permission.

However, if the product of choice is particularly difficult to make and advances in manufacturing process have not been published, an organisation may maintain its commercial advantage towards the end of the product's patent life by filing a new, more efficient, manufacturing process patent. Once the patent expires, any competitors can manufacture and sell the product but they cannot use any newly patented processes without a licence and are, therefore, at a competitive disadvantage. This is not a usual situation as manufacturing expertise is often sufficient for process patents to be bypassed, but the protection of the paraquat patent position by ICI (now Syngenta) is an often-quoted example as paraquat is particularly difficult to make and improvements in the manufacturing process that have been patented by the inventor will help to maintain Syngenta's competitive advantage.

One area where process patent protection has been shown to be advantageous is in the resolution of components of racemic mixtures of isomers where it is known that one isomer is more biologically active than others. An example is the resolution of the isomers of dichlorprop and mecoprop by BASF. It was well known that only one isomer of both compounds was herbicidally active, so the application of 100 g of racemate ha ^{1} meant that only 50 g active ingredient ha ^{1} was being applied. The manufacture of the pure (*R*) isomer therefore gave advantages in terms of cost of intermediates in manufacture, cost of packaging and subsequent disposal, and rate of chemical applied per unit area with no loss of herbicidal efficacy.

Use patents

When a new compound application is filed which covers a series of compounds within a specified general formula, it is a usual practice that all known uses of the compounds claimed be described. There are occasions, however, when companies will be searching for biological effects that originators of patents may not have considered within their discovery research programme.

A typical example may be a pharmaceutical company searching for new analgesics and selecting a series that meets its objective. Subsequently, an agrochemical company may find herbicidal activity in compounds contained within the general formula but neither specifically exemplified nor individually claimed. A patent can then be filed on a selection of compounds from within the original patent, claiming a new use for those selected. However, because such a patent is subject to the dominant patent of the pharmaceutical company, the agrochemical company cannot manufacture or sell without a licence from the owner of the dominant patent while the patent is still in force. Neither can the holder of the dominant patent sell any of the newly selected compounds as a herbicide without a licence from the agrochemical company.

A use patent can also cover a method of use. An example of this might be the application of a herbicide twice at half the usual recommended rate, thereby providing longer-term control of weeds that are treated at an earlier growth stage. Once again the advantage is that only the patent holder can recommend that the product be used in this way. However, the person most likely to infringe this type of patent is the farmer, and it is not in the best interest of a crop protection company to sue its customers. The main area of litigation around use patents is contributory infringement, which is encouraging or giving the means to infringe.

Formulation patents

When a new compound patent is filed it is important to include within it an indication of how the invention can be implemented (reduced to practice). In the case of an agrochemical patent, this will usually include the description of one or more formulations. The reasons for doing this are many, but the priority is to ensure that no competitor can put in a claim for a particular formulation type for your product, thereby preventing you from marketing that formulation. It is usual to make quite general claims that will count as a publication and thereby prevent any claim for novelty. There are situations where an advantage through formulation may justify the filing of a specific formulation patent. An ester of an alkanoic acid that gives increased solubility, or allows the formulation of a product as a wettable powder or other previously unobtainable formulation, is an example.

Mixtures

It is unusual for a crop protection patent for a new product not to include a statement that allows for the mixture of the invention with other products in use. Again, there are many reasons why these statements are included, but they do ensure that the claim of mixtures has been published. It is true that the inventor can do nothing with the combinations if one component is still covered by patent by a competitor but such statements also ensure that the competitor fails to obtain control of its product in combination with yours.

The most usual statement is along the lines that members of formula 1 (or whatever description is included in the patent claim to describe the chemistry) can be mixed with compounds such as.... There is no claim for an invention in such a statement, merely notification that the invention can be mixed with other chemicals. For this reason it is not necessary to include biological data.

It must also be remembered that new products will be released throughout the commercial life of your product and these mixtures will not have been covered in your dominant new compound patent because they were not invented when it was filed. In this case there must be a real commercial advantage in filing a new patent, with its associated costs, on a combination of the two components. When it has been decided that there is a commercial reason for acquiring control of this combination, there is a requirement that an inventive step be included. Traditionally, the Colby formula has been used to show more-than-additive effects. For example, if component A gives 40% control of your target and compound B gives 25% and if the two components act at different sites, the expected response will not be the simple addition $40 + 25 = 65\%$; it will be 40 plus 25% of the remaining 60% unaffected by compound A, which gives $40 + (60 \times 0.25) = 55\%$. Hence, any effect that is consistently higher than 55% control by the components of the mixture will be unexpected, 'not obvious' and inventive.

Intermediate patents

Any compound that is novel and that is used in the basic process in the manufacture or synthesis of a new compound can be patented. It is very unlikely that such compounds would not be mentioned in a dominant new compound patent and as such they would be covered by that patent and also published within that filing. To be patentable, new intermediates in analogous processes forming new products must make structural contributions to the end product and must not be obvious.

Patenting of genes

All of the information discussed above is on the filing of new patents relating to chemistry. Increasingly, there is interest today in patents that are concerned with molecular biology and individual genes. This is a very new area of law and it is not clear yet what is allowable and what is not. However, some decisions are being made.

Fully sequenced genes whose protein function is known are patentable. At present it is possible to file patents that claim

(1) a process that confers a biological characteristic, e.g. resistance to fungal infection or insect attack
(2) a complete gene sequence that codes for a protein with a known function
(3) a transformed cell
(4) a vector or transcript
(5) a protein of known function
(6) higher organisms, including plants and animals (but not man)
(7) processes for making and modifying them

Partial gene sequences and gene fragments are not patentable if their products are not known or if they have no known function. In the USA, all of the above are covered by patent law, whereas in the EU plant varieties are not patentable but breeders are protected by plant breeders' rights. However, if a gene is used to transform a plant, then the human intervention that makes that transformation possible is patentable, as is the gene or gene construct. As the transgenic plant contains the patentable material and is not describable as a specifically new variety with properties that distinguish it from other varieties, it too is patentable.

Research use of patents

A patent, once granted, allows the inventor to commercialise the invention without fear of competition from a third party. However, there is a common interpretation that research is exempt from these patent restrictions. As such, agrochemical companies will often make very small quantities of a competitor's newly patented compounds to establish how effective these compounds are in their screens. Under the terms of UK and European patent law, work carried out for 'experimental purposes' on patented subject matter does not constitute an infringement of the patent concerned. The definition of 'experimental purposes' is clearly very important. It covers fundamental work that includes efforts to modify or improve the invention with no commercial goal in mind.

Conclusion

The discovery and commercialisation of a new herbicide is a complex process that demands close interaction between a wide range of scientific disciplines. It is essential that the commercial targets are well known and understood by the discovery team in order that relevant and reliable screens can be established that will allow high throughput of compounds and rapid feedback of data to synthesis chemists and biochemists. Synthesis should take into account the ideas of the physical chemists and learn from the target elucidation undertaken by the biochemists working with molecular biologists in functional genome analysis.

A screen is only as good as the data it generates, and the interpretations of these data are only of value if the questions asked of the test are understood. It is of no value to establish a test that selects all active compounds regardless of the commercial value of that activity. A good screen will identify 'value' actives with a real chance of leading to a commercially significant product.

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Chapter 7
Herbicide Legislation and Regulation

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Introduction

The very nature of pesticide products, designed to control harmful organisms, means that they need to be highly regulated in order to ensure that they do not have any adverse effects on operators using them, on the environment or on consumers of treated produce. Registration systems usually also require efficacy to be demonstrated, ensuring that only products that are sufficiently effective are authorised and so helping to minimise pesticide usage. Different registration systems apply in different countries, although there are several initiatives currently being pursued with the objective of harmonising the processes between countries.

The general requirements in terms of tests and studies required to demonstrate safety and efficacy are broadly similar in many countries throughout the world and are substantial, with possibly more data being required for pesticides than for any other class of chemical due to the complexity of the risk assessment. These requirements are becoming more stringent and will increasingly reduce the number of products available to growers as older pesticides are re-assessed to modern standards.

This chapter will consider the legislation and regulatory procedures involved in the control of pesticides, focusing primarily on the UK and European systems but also considering the sytems in place in the USA, Canada and other countries. Current initiatives in relation to the harmonisation of these processes will also be considered, as well as the possible consequences of the present high level of activity in the field of pesticide regulation.

Legislation in the UK

PSPS and ACAS

The rapid and intensive development of pesticides in the 1940s, particularly insecticides and herbicides, resulted in two Working Party reports being commissioned to consider the possible risks arising from the use of toxic substances in agriculture.

As a result of the deaths of several agricultural workers in Britain following the use of the herbicide dinitro-*ortho*-cresol (DNOC), a Working Party was established to examine the safety of workers using agricultural chemicals that were toxic or harmful to humans. The Working Party report, published in 1951, gave rise to the Agriculture (Poisonous Substances) Act of 1952. A second Working Party was established to consider the risk from the use of toxic substances on agricultural products and stored food products. The second report, published in 1953, recommended that an advisory body be established to consider these risks and that new pesticides should be cleared by the appropriate Government Departments before their use in the UK. Thus, in 1954, an Advisory Committee on Pesticides (ACP) consisting of independent scientific experts was formed to provide recommendations on the safe use of pesticides. To exercise the new controls two separate, non-statutory regulatory schemes were then established.

The Pesticides Safety Precautions Scheme (PSPS) was established in 1957 to provide an assessment of the safety of the products and risks to operators, consumers and wildlife associated with their use. Under the Scheme, no pesticide product could be placed on the market until conditions that resulted in safe use had been agreed by the Government and a ‘clearance’ for the product had been issued. At around the same time the Agricultural Chemicals Approval Scheme (ACAS) was established to consider the efficacy of the products.

Although PSPS was a voluntary scheme, it represented a formally negotiated agreement between the Government and various industry groups including, *inter alia*, the British Agrochemical Association (BAA), the British Crop Protection Council (BCPC) and the UK Agricultural Supply Trade Association (UKASTA), together with farmers’ and growers’ unions and associations. This resulted in a very high compliance with the Scheme. Also, although PSPS and ACAS were operated independently, they were in fact linked in that a product would not be considered under ACAS unless it had received a clearance under PSPS.

Although there was no legislation directly controlling the use of pesticides *per se*, several other regulations impinged on their production and use. These included the Health and Safety at Work Act (1974) and the Health and Safety (Agriculture) (Poisonous Substances) Regulations (1975), the Poisons Act (1972), the Rivers (Prevention of Pollution) Acts (1951–1961) and the Control of Pollution Act (1974).

Following a report from the Royal Commission on Environmental Pollution, recommending that both safety and efficacy be regulated together under a single system, the Control of Pesticides Regulations 1986 (COPR) were introduced under the Food and Environment Protection Act of 1985 (FEPA) (UK, 1985, 1986).

FEPA and COPR

In relation to pesticides, the aims of FEPA were to protect the health of human beings, creatures and plants, to safeguard the environment and to secure the safe, efficient and humane control of pests. A further objective was to make information about pesticides available to the public. These aims were to be realised through various new powers conferred on Ministers in relation to the distribution and use of pesticide products, which were implemented via the new regulations.

The Department for Environment, Food and Rural Affairs (DEFRA; formerly MAFF) and several other Government Departments are jointly responsible for the approval of all pesticides, although the responsibility for the registration of the products is divided between the Pesticides Safety Directorate (PSD) and the Health and Safety Executive (HSE). PSD, an Executive Agency of DEFRA, deals primarily with the registration procedures and policy relating to products approved for use in agriculture, horticulture and forestry, while HSE's Biocides and Pesticides Assessment Unit deals with other, more industrial products such as antifouling products, surface biocides and wood preservatives and treatments. It is DEFRA that deals with the approval of agricultural herbicide and amateur weedkiller products in the UK.

COPR came into force on 6 October 1986 and since that date it has been illegal to place a pesticide product on the market unless the safety and efficacy of the product have been assessed and an approval has been issued. Approvals are the means by which Ministers set the specific conditions on the sale, supply, storage, advertisement and use of individual pesticide products; there are three basic levels of approval. The first is the *experimental permit*, based on a limited data package, which enables further testing and development under controlled conditions. *Provisional approvals* represent the first commercial level of approval and are granted following the evaluation of a comprehensive data package indicating acceptable uses in terms of risks to humans, wildlife and the environment and the efficacy of the product. These are usually time-limited, however, to allow for the provision of further, confirmatory data required to complete the risk assessment. *Full approvals* are issued for an unstipulated period following the completion of the risk assessment.

As well as specific approvals controlling the marketing and use of pesticides, there are also a number of general rules, or Consents, which set out basic conditions applying to all products in relation to advertisements, use (including tank-mixing) and aerial applications.

Until the introduction of COPR, although most label-recommended uses had been considered under PSPS and possibly ACAS, it had been possible and legal for growers to use any pesticide product on any crop. Under the Regulations, however, only those uses that had been considered and approved in terms of both safety and efficacy could be practised. It soon became clear that pesticide manufacturers would not necessarily generate the required residues and efficacy data to obtain approval for the full range of possible uses, particularly those of limited commercial potential, i.e. for crops grown on a small area or those not traded internationally.

This led to the establishment of the off-label approval system comprising both specific off-label approvals (SOLA) and the 'Long Term Arrangements for

Extension of Use', whereby products approved for use on certain crops can also be used on other, similar crops at the grower's own risk (Chapter 19). For such off-label uses, the risk assessment relating to operators, consumers and the environment is extrapolated from the data available for the similar approved use, and efficacy data are not considered – hence the use is at the grower's own risk.

There are several authorities involved in the enforcement of COPR. HSE is responsible for the majority of the enforcement activity relating to the supply, storage and use of pesticides. DEFRA is, however, responsible for the investigation of any wildlife poisoning incidents involving pesticides under the Wildlife Incident Investigation Scheme (WIIS) and also takes the lead in the monitoring of pesticide residues in food.

As before, given the number of external factors to be considered in the risk assessment for pesticides from their production and distribution through to use and disposal, various other legislative controls impinge on the process. Worthy of particular mention are the Control of Substances Hazardous to Health Regulations 1994 (COSHH) and the various Maximum Residue Level (MRL) Regulations.

The COSHH Regulations, made under the Health and Safety at Work Act 1974, aim to control the risks to operators and workers arising from substances considered hazardous to health, including those from the use of pesticides on farms, in factories, by local authorities etc.

The MRL Regulations establish maximum levels of pesticide residues that may be left in crops, foods and feedstuffs in accordance with European Directives. These MRLs are defined as the maximum concentrations likely to occur in food or feed following the use of the pesticide according to good agricultural practice (GAP). As such, they are primarily intended as a check that GAP is being followed. It is important to note that they are not safety levels, and residue levels in excess of the MRLs do not automatically imply a hazard to health.

The legislation and registration procedures mentioned above relate to the control of agricultural- and amateur-use pesticides in the UK, and are still extant at the time of writing. Of increasing importance, however, is the European Legislation introduced in the 1990s.

European legislation

Directive 91/414/EEC

The fact that Member States of the European Union were operating widely different schemes in relation to the control of pesticides was considered to represent a possible barrier to trade, in direct contravention of one of the founding principles of the community. In 1991, therefore, Council Directive 91/414/EEC concerning the placing on the market of plant protection products was adopted and entered into force on 25 July 1993 (EEC Council, 1991). This

Directive formed the framework for a European-wide regulatory system for the evaluation and authorisation of plant protection products and the active substances in them.

The plant protection products covered by 91/414/EEC are equivalent in many respects to the products approved by DEFRA (formerly MAFF) in the UK, including agricultural herbicides and amateur-use weedkillers. A similar Directive, 98/8/EC – the Biocidal Products Directive, deals with the products generally covered by HSE in the UK (European Parliament & EC Council, 1998). The further detail given below relates, in the main, to the procedures established under 91/414/EEC.

A two-stage registration process has been established through the Directive, with the consideration of the acceptability of active substances at community level while the authorisation of specific products and uses is dealt with by the individual Member States. Thus, Annex I to the Directive, the list of active substances deemed acceptable in terms of risks to humans, animals and the environment which may be included in pesticide products for use in the community, is the prime focus of the European regulatory system.

In order to demonstrate acceptable uses in terms of risks to users, consumers and the environment, a considerable amount of data must be provided by the manufacturer. The data requirements relating to active substances and plant protection products are given in Annexes II and III of the Directive respectively, and relate to six discrete areas of the risk assessment: physical and chemical properties; environmental fate and behaviour; ecotoxicology; mammalian toxicology; residues; and (Annex III only) efficacy.

In the same way that the regulatory procedures to be adopted by Member States needed to be harmonised, so too did the decision-making processes relating to the safety and efficacy of products at the national level. The basic rules to be observed when conducting risk assessments are established by way of Article VI of the Directive, which sets out the so-called ‘uniform principles’ for the assessment of the acceptability of products. The details of the uniform principles were published in Directive 97/57/EC (EC Council, 1997).

The basic premise of the Directive is that plant protection products should not be authorised unless the active substance has been included in Annex I. However, it was recognised that the actual decision-making process relating to inclusion or not in Annex I may take some time, and so for new active substances provision was made under Article 8.1 for the possible authorisation of products at Member State level for up to three years before the decision on Annex I inclusion is taken.

The EC review programme

In establishing a harmonised registration procedure for the regulation of pesticides across Europe, it was also recognised that thousands of products containing around 800 active substances had already been authorised in the different Member States. In order that these, too, should meet the requirements of the new standards defined in the Directive, provision was made for the re-evaluation of all those active substances on the market at the time the Directive came into force, the so-called 'existing' active substances.

Article 8.2 of the Directive provides a derogation that allows Member States to continue to regulate products containing existing active substances in accordance with existing national legislation for a period of ten years from the date of the Directive coming into force, i.e. until 25 July 2003. It was probably optimistic, to say the least, to envisage that the entire review of 800 active substances could be completed within ten years, particularly when considering the diverse range of regulatory systems in place across Europe at the time of the adoption of the Directive and the complexity of the risk assessment for pesticides. Nevertheless, ten years was all that was provided for in the Directive, with this period expiring in July 2003.

This review programme for these existing active substances is being effected through a series of Commission Regulations. The original plan was to publish annual lists of active substances for review and the first review regulation, Regulation 3600/92, listed the first 90 active substances to be reviewed and detailed the procedure to be followed (EEC Commission, 1992). It required manufacturers to notify their intention to support an application for the inclusion of an active substance in Annex I. Regulation 933/94 provided details of the notifiers for each of the active substances supported in the review and identified the *rapporteur* Member State for each active, whose function it was to evaluate the data provided to support Annex I inclusion, prepare a report of the evaluation and make a recommendation with regard to inclusion or not in Annex I (EC Commission, 1994). Following the accession of Austria, Finland and Sweden to the community, the *rapporteur* responsibilities were redistributed by way of Regulation 491/95 (EC Commission, 1995a).

Progress with the evaluation and decision-making for the first list of actives for review was not as rapid as originally expected and a new approach was adopted with the second review Regulation. Regulation 451/2000, which came into force on 1 March 2000, is split into two parts (EC Commission, 2000). The first part provided details of the second list of 148 active substances for review, and the deadlines and procedures to be adopted. The second part of the Regulation initiated the review of all the remaining active substances on the market in the third phase of the review programme, setting a deadline for commitments to support the active substances in future reviews. For both the second list and the third phase of the programme, the Regulation made it clear that all active substances not supported would be withdrawn from the market by 25 July 2003. The second Regulation also introduced a provision to charge fees to cover the costs of the work involved, and also established possible derogations for 'essential uses' important to agriculture.

Within Europe, as in the UK, other legislation also impinges on the production and use of pesticides, in particular Directives 67/548/EEC and 1999/45/EC concerning the classification and labelling of active substances and preparations, Directive 90/220/EEC concerning the release into the environment of genetically manipulated organisms, Council Directive 86/609/EEC relating to the protection of animals used for experimental purposes and the various MRL Directives. Also of particular importance when considering the acceptability of pesticide uses is Council Directive 80/778/EEC, relating to the quality of water intended for human consumption (EEC Council, 1980).

All Member States have implemented Directive 91/414/EEC, and in the UK this has been done by way of the Plant Protection Products Regulations 1995 (as amended) (PPPR) (UK, 1995). These define the products that are subject to regulation and prescribe the approvals required before any plant protection product may be placed on the market or used following inclusion of the active substance in Annex I of the Directive. In addition, the Plant Protection Products (Basic Conditions) Regulations 1997 (BCR) apply control and enforcement provisions similar to those of COPR to plant protection products, thus ensuring that the enforcement powers for products authorised under PPPR are equivalent to those under COPR (UK, 1997).

The regulatory procedure

Although there is basically one pesticide registration system across Europe following implementation of the Directive in all Member States, slightly different approaches are taken for new and existing active substances. A flow diagram depicting the general procedure is provided in Fig. 7.1.

For new active substances, an application for Annex I inclusion is submitted to the *rapporteur* Member State, which is chosen by the applicant. The application is submitted in the form of a 'dossier' which contains all the data necessary to allow for the assessment of safety and efficacy of the uses, as set out in Annexes II and III of the Directive. The European Commission has prepared detailed guidance for the preparation of such dossiers (EC Commission, 1997a). Following receipt of the dossier, the *rapporteur* conducts a completeness check on behalf of the Community, ensuring that all the information required for the risk assessment has been submitted in the dossier. The dossier must be agreed as complete by all 15 Member States in the Standing Committee on Plant Health (SCPH) and a Commission decision announcing the completeness must be issued, before the detailed evaluation of the dossier begins or any provisional authorisation under Article 8.1 of the Directive can be issued.

For existing active substances, the process is initiated through the publication of a Commission Regulation, listing the active substances involved and establishing a deadline by which manufacturers must notify their intention to support the active substance in the review. Following the receipt of the notifications, a further Regulation is published giving details of the active substances supported and the notifiers involved for each. This Regulation also announces the designated *rapporteur*, and establishes the deadlines for notifiers to submit the dossiers

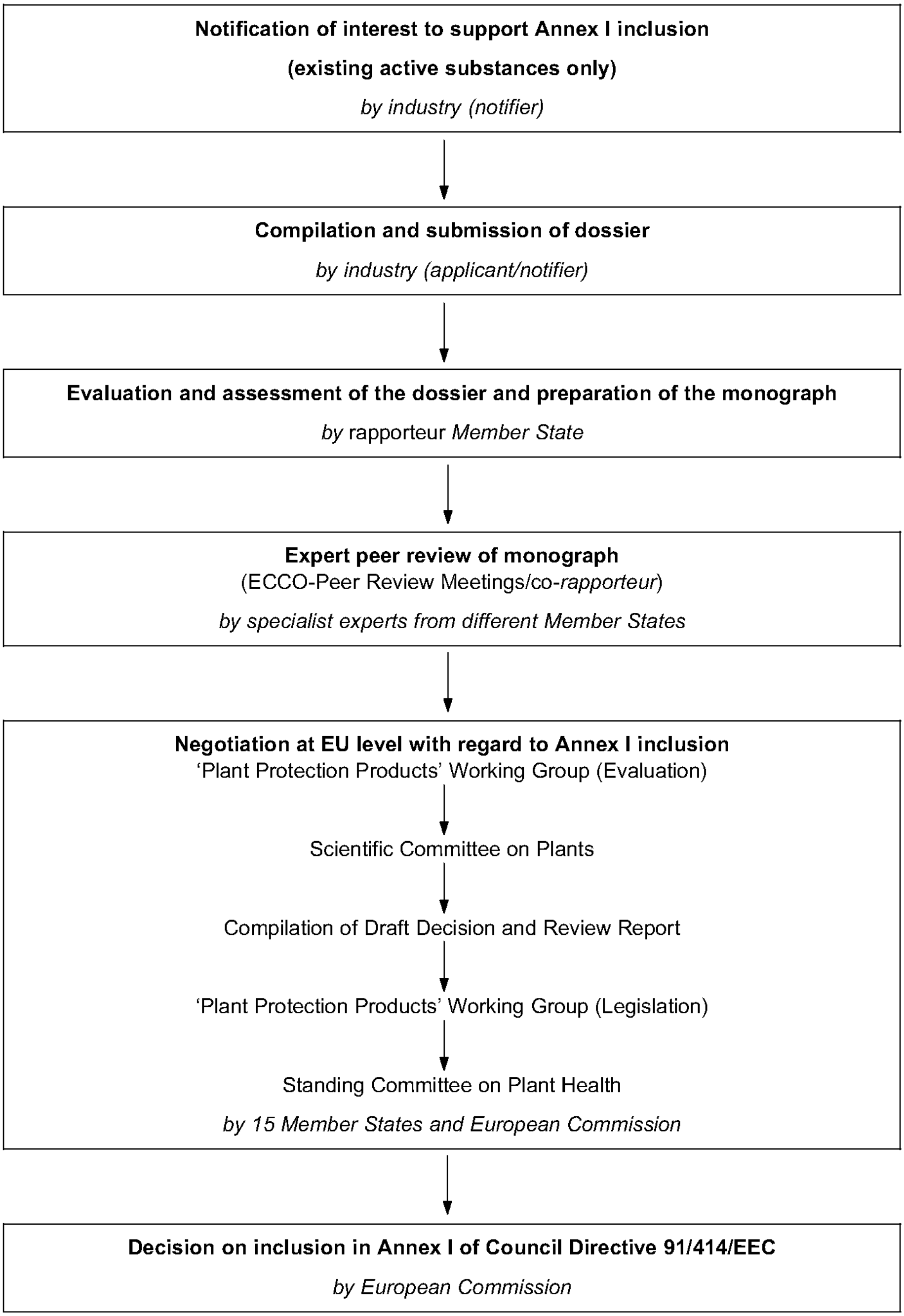

Fig. 7.1 Registration procedure for active substances in plant protection products within the European Community under Council Directive 91/414/EEC.

and for the *rapporteurs* to prepare the reports of the evaluations, or 'monographs'.

Following receipt of the dossier the *rapporteur* has, in principle, 12 months to prepare the monograph. Again, the European Commission has produced detailed guidance for Member States on the preparation of monographs (EC Commission, 1997b).

Once the monograph is prepared, it is submitted to the European Commission for consideration within the framework of the SCPH. For the earlier monographs it was soon apparent that there was a need to obtain a wider, pan-European view of the monograph that had been prepared by a single Member State, in order to facilitate decision-making by 15 Member States in the SCPH. The European Commission Co-ordination (ECCO) peer review programme, organised jointly by the Biologische Bundesanstalt für Land- und Forstwirtschaft (BBA) in Germany and the Pesticides Safety Directorate (PSD) in the UK under contract to the European Commission, was established to undertake this function. Under this programme, monographs are examined by technical experts from different Member States in specific meetings organised to examine each of the specialist scientific disciplines covered by the monograph, e.g. mammalian toxicology, ecotoxicology, residues etc., in turn. It is clear that, eight years into the programme, some form of wider peer review of the evaluation of a single Member State is still required to help achieve a consensus of views from the 15 Member States. This may not have to be by consideration at ECCO peer review meetings, however, and could equally be achieved by way of a co-*rapporteur* system, where the *rapporteur* liaises with other Member States, preferably during the preparation of the monograph.

Following peer review, the monographs and proposed decisions with regard to Annex I inclusion are forwarded for consideration at the two Commission Working Groups on 'Evaluation' and 'Legislation', where all 15 Member States are represented. The 'Evaluation' Working Group concentrates on the technical aspects of the evaluation, finalising the text of the monograph and resolving any outstanding issues. It also identifies any key concerns that should be drawn to the attention of the independent experts on the Scientific Committee on Plants (SCP).

The final stage of the process is consideration by the 'Legislation' Working Group of the proposed decision (in the form of a draft review report) and the opinion of the SCP. This takes into account the wider, more political implications of the proposed decision.

Eventually, a vote will be taken in the SCPH on the proposed decision, which would then be formally adopted by the European Commission. Positive decisions to include active substances in Annex I are published in the form of amending Directives amending 91/414/EEC to include the active in Annex I. These set out the technical specification of the active substance and any restrictions to be associated with its use. They also provide deadlines by which products already authorised by the Member States must be checked for compliance. Decisions not to include the active substance in Annex I are published in the form of Commission decisions to withdraw the active substance and plant protection products containing it from the market; they set out deadlines for the revocation actions required to be taken by the Member States.

Risk assessments

In the early days of pesticide registration the amount of data required to support a registration and the risk assessment conducted using those data was very limited, basically concentrating on the toxicology package for the purposes of hazard classification and labelling. Today, however, there is a far better understanding of the complex interactions between chemicals and animal and plant systems and the environment. This, together with the rapid development of appropriate scientific techniques to determine and quantify those interactions, has resulted in a considerable amount of data and complex risk assessment being required to support the registration of pesticide products. The modern standard for a data package to support the registration of a pesticide in Europe is defined by the data requirements set out in Annexes II and III of Directive 91/414/EEC, which also identify the relevant test guidelines that should be followed for particular studies. The rules to be applied when performing the risk assessments based on these data are established in Annex VI of the Directive, the 'Uniform Principles'.

All the tests and studies submitted must be performed in accordance with recognised test guidelines and in compliance with Good Laboratory Practice (GLP) where appropriate. Since their development in 1981, the test guidelines established by the Organisation for Economic Co-operation and Development (OECD) have become the internationally recognised (OECD, 1981). Many of the test guidelines referred to in the Directive are for EC methods that have been adapted from the OECD guidelines. GLP is intended to ensure the quality and validity of test data and covers the conditions under which laboratory and field studies are planned, conducted, monitored and reported. A guideline has been issued detailing the applicability of GLP to all Annex II and III data requirements, and all studies initiated after certain specific deadlines must be conducted in accordance with GLP or they will not be accepted (EC Commission, 1995b).

Risks to humans

A comprehensive data package relating to mammalian toxicology must be generated and submitted in order that the risk to humans, particularly the operators using the product and consumers eating treated produce, can be assessed.

An acute toxicity package, comprising acute oral, dermal and inhalation studies, skin and eye irritation and sensitisation studies, is required for the active substance and the formulated product. The results of these studies identify effects following a single exposure to the active substance and are used primarily for hazard classification of the products.

Data on the toxicokinetics of the active substance (rate and extent of absorption, distribution and potential for accumulation, rate of excretion and metabolism) provide information on what happens to the active substance in animal systems, including the identification of any problematic metabolites that may be formed.

Short-term acute studies are undertaken via oral, dermal and inhalational routes, primarily to identify any major effects on specific organs and also to provide guidance on the range of doses that should be used in the long-term studies. A key objective of the toxicological assessment is to establish 'no adverse effect levels' for any ill or adverse effects that occur. The No Observed Adverse Effect Level (NOAEL) is the highest dose in a study that did not result in any adverse effect.

The NOAEL from an appropriate sub-acute study is usually used in establishing the acceptable operator exposure level (AOEL), against which operator, worker and bystander exposures are assessed. The AOEL is intended to define a level of exposure to which operators could be exposed over relatively short periods without suffering adverse effects.

The NOAEL from acute toxicity studies would be used, where relevant, to set the acute reference dose (ARfD) for acute dietary risk assessment purposes. The ARfD represents the amount of the compound that could be safely consumed in one meal or one day.

Long-term studies are required to determine the chronic toxicity and carcinogenic potential of the active substance following repeated exposure. Multigeneration and reproductive studies are undertaken to identify any effects of the compound on the reproductive capacity in the animal tested or any deleterious effects in their offspring. Genotoxicity studies are conducted to determine any effects the compound may have at the gene or chromosome level, while teratology studies are required to identify any developmental effects in the fetus.

It is the appropriate NOAEL from these longer-term studies that is used to establish the acceptable daily intake (ADI) value for the active substance. The ADI represents the amount of active that could be consumed every day for a lifetime in the practical certainty that, on the basis of all known facts, no harm would arise, and it is this value which is utilised in the chronic dietary risk assessment.

There are two key elements in estimating risk to humans from the use of the active substance: the possible risks associated with consumption of the active substance, and the possible risk to operators and workers.

A comprehensive package of residue data is required to be provided, covering all the edible crops on which the product is to be used. These data are then used in conjunction with food consumption data to provide estimates of dietary exposure, which are then compared with the ADI or ARfD to determine the acceptability of the proposed uses in terms of the risks associated with possible consumption of the active substance. In some areas, the risk assessment procedures are being further refined to consider the aggregate effects of the same substance from various sources or the combined effects of several active substances with similar modes of action.

The risk to operators applying pesticides and to workers involved in handling treated crops, as well as to bystanders who may be inadvertently exposed in areas adjacent to the area being treated, is evaluated using actual exposure monitoring data where available, or realistic estimates from a validated model. A compound will not be included in Annex I where predicted operator, worker or bystander exposure exceeds the AOEL. Different assessments must be undertaken for each formulation and use, and specific product–crop combinations will not be authorised where the AOEL is exceeded.

Risk to the environment

The possible effects that the use of pesticides may have on the environment were highlighted with the publication of *Silent Spring* (Carson, 1962), which drew attention to the possible concerns arising from persistence and biomagnification of organochlorine pesticides in the food chain. Since then, the most significant advances in terms of risk assessment methodologies for pesticides have been in the area of the environmental risk assessment. An enormous battery of tests and studies are now required to be performed to provide data relating to the fate and behaviour of the active substance in the environment and effects it may have on fauna and flora.

The fate and behaviour, or environmental chemistry, data are provided in order to predict the movement of the chemical in the various compartments of the environment. Data relating to the rate and route of degradation in soil, water and air are required in order to determine predicted environmental concentration (PEC) values for use in the assessment of possible effects on wildlife. Some of the end-points derived from the fate and behaviour assessments may be used as acceptability criteria in their own right, e.g. end-points indicating persistence of the compound in the environment or the potential for long-range transport in the air.

A comprehensive package of toxicity tests on a range of non-target species, both fauna and flora, are conducted in order that the possible short- and long-term effects on wildlife can be assessed. The biological end-points from these studies are used in conjunction with the PEC values derived from the fate and behaviour data to provide toxicity exposure ratios (TERs) for non-target species.

To assess the possible effects on birds or bird populations, data from acute toxicity tests, short-term dietary studies and reproductive toxicity tests are required, in addition to any details of actual incidents that may have been reported. A considerable amount of data must also be provided to address the possible risk to the aquatic environment. Data on the toxicity to fish (short- and long-term) and the potential for bioaccumulation in fish are required, as well as data relating to the effects on aquatic invertebrates and higher plants, algae and sediment-dwelling organisms. These data must assess the potential effects arising from contamination of ground or surface waters from leaching or run-off, or from spray drift.

To assess the potential risk to terrestrial non-target organisms, data on the effects on bees, non-target and beneficial arthropods and earthworms are required.

All these data are used to determine the likely impact on non-target fauna and flora from single or repeated exposure, in terms of possible effects on individuals, populations or communities, and to identify any conditions or restrictions that need to be imposed to reduce those effects to an acceptable level.

Efficacy

As well as identifying the possible risks to humans and the environment that may arise from the use of a pesticide, an equally important consideration is whether or not the products actually work. Efficacy data are required to evaluate the nature and extent of the benefits that arise from the use of the product and to determine the minimum effective dose. Information on the nature and extent of the benefits could be weighed against the potential risks when completing the overall risk assessment, while data on the minimum effective dose help in minimising pesticide usage.

Data relating to the effectiveness of the product, the possible occurrence of resistance and the effects on yield in terms of both quality and quantity are all part of the assessment. Phytotoxicity data are also required to determine if there may be any undesirable or unintended effects on different varieties of the target plants, adjacent crops or succeeding crops. This latter point, potential effects of any residual amounts remaining in the soil on following crops, is of particular importance in the assessment of the newer, highly active sulphonyl urea herbicides, for example.

With the implementation of Directive 91/414/EEC, quality standards in relation to efficacy field trials were established with the introduction of the requirements for Good Experimental Practice (GEP) and Official Recognition. GEP introduces an agreed quality standard that previously did not exist for efficacy field trials, in line with GLP for laboratory studies, and that was augmented by the requirement that these studies be conducted by official, or officially recognised, organisations.

For efficacy trials, standard test guidelines have been established by the European and Mediterranean Plant Protection Organisation (EPPO), and all trials must be conducted in accordance with those guidelines (EPPO, 1997–1999, and as subsequently updated).

Legislation in other parts of the world

Although the detailed data requirements, legislation and government organisations responsible for the procedures may be different, the general requirements and registration processes are often similar in many countries.

United States of America

In the USA, the first federal legislation relating to food quality was passed in the form of the Pure Food and Drug Act of 1906. The first federal legislation dealing directly with pesticides appeared in the form of the Insecticide Act of 1910. Administered by the US Department of Agriculture (USDA), this aimed to control the manufacture, sale and transport of insecticides and fungicides.

The Federal Food, Drug and Cosmetic Act (FFDCA) of 1938 included the regulation of pesticides in food and the assessment of pesticide tolerances, the equivalent of MRLs in Europe (USA, 1938). The present legislation under which pesticides are regulated is the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) which, when passed in 1947, extended the controls of the original Insecticide Act to herbicides and rodenticides and required that all pesticides must be registered through the USDA (USA, 1947). Under this legislation, although all products had to be registered, registrations could not be refused. However, with the general increase in concern surrounding the use of pesticides in the early 1960s, FIFRA was amended in 1964 to give the USDA the power to refuse, revoke or suspend registrations to protect human health.

In 1970, the responsibility for pesticide regulation under FIFRA was transferred to the newly established US Environmental Protection Agency (US EPA), as was the authority to establish tolerances on food under FFDCA from the Food and Drug Administration. Following a total review of the regulatory system in 1972, FIFRA was amended to separate out general- and restricted-use products and to require that registrants supply data to demonstrate that the product would present ‘no unreasonable adverse effects’ to crops, non-target organisms or the environment. In 1988, a further amendment was passed requiring the re-registration programme for active ingredients registered before 1984 to be accelerated.

The introduction of the Food Quality Protection Act (FQPA) in 1996 brought about dramatic changes in the risk assessment procedures under FIFRA and FFDCA (USA, 1996). FQPA required the EPA to follow strict criteria for the assessment of pesticides, including additional protection measures for infants and children, and the assessment of all risks posed by pesticides with similar modes of action. The safety standard was also refined, so that the EPA is now required to establish that a pesticide poses a ‘reasonable certainty of no harm’ rather than ‘no unreasonable adverse effects’ before it can be registered. FQPA also requires the EPA to accelerate the registration of ‘reduced risk’ pesticides.

In terms of the re-registration programme, the EPA is required to reassess pesticides that were registered before 1 November 1984, to ensure that they now meet with the more stringent standards imposed through FQPA. As part of this process, priority has been given to pesticides intended for use on food or feed, and the EPA is required to reassess over 9000 tolerances. Reregistration Eligibilty Decisions (REDs) and Fact Sheets are the published results of the EPA's regulatory reviews under this programme.

In line with Europe, in evaluating a pesticide registration application the EPA assesses a wide variety of potential human health and environmental effects associated with the use of the product. The applicant must provide a broad range of data from tests performed in accordance with EPA guidelines.

One of the key focal points of the FQPA is the establishment of tolerances. As with MRLs in Europe, these are not enforcement levels based on safety but enforcement levels established to identify the misuse of a pesticide. The risk assessment conducted when setting tolerances under the new regime must include aggregate exposure (exposure to the same compound from different sources), cumulative exposure to pesticides with similar effects, any increased susceptibility to infants, children or other sensitive sub-populations and any endocrine disruption potential.

Canada

In Canada the first legislation dealing with the regulation of pesticides was the Agricultural Pests Control Act (APCA) of 1927. This was amended in 1939 to become the Pest Control Products Act (PCPA). In 1969, a revised PCPA was introduced and brought into force through the adoption of Regulations in 1972 (Canada, 1985a). Both ACPA and PCPA were administered by the Department of Agriculture, although following the revision of PCPA and the introduction of the Regulations, the Departments of Health, Environment and Natural Resources (Forestry and Fisheries) also became responsible. The Department of Health was also responsible for the Food and Drugs Act (FDA), which was initially introduced in the 1920s and controlled the setting of maximum residue limits for pesticides in food (Canada, 1985b).

Following a review of pesticide regulation in 1990, the Pest Management Regulatory Agency (PMRA) was established as part of Health Canada in 1995, taking over complete responsibility for the administration of PCPA. The Agency is responsible for the protection of human health and the environment, but also responsible for ensuring the necessary pest control measures are available to those that need them.

Whilst the primary controls are established under the PCPA, there is additional legislation impacting on the use of pesticides at the federal, provincial and municipal level.

As in other countries, a comprehensive data package must be submitted to allow the complete risk assessment, and all studies must be conducted to the appropriate OECD test guidelines and to GLP standards where necessary. In addition, for certain applications the dossier submitted to Canada must contain a comprehensive data summary compiled in accordance with the European Community dossier guidelines, i.e. based on the EC Directive Annex II tier II format, and must also include a summary assessment document based on the EC Annex II tier IV format.

A key component of the Canadian system is the screening process, introduced to improve the efficiency of the regulatory process by ensuring that only complete and properly formatted and organised submissions are accepted into the evaluation process. A special Submission Screening Section has been established to check applications once they are accepted into the system, where the submission is screened within a limited timeframe. Where no deficiencies are identified, the submission is accepted and forwarded for evaluation. Where deficiencies are identified, however, the applicant is informed and given a limited time to submit the outstanding information. If no response is received, or the response is inadequate, the submission is rejected and returned to the applicant at the expense of the applicant. A completely new submission is then required to be submitted, should the applicant still wish to pursue the application.

Most countries employ some form of 'sift' or completeness checking system, but the more rigorous approach adopted in Canada may well become the future model, given the need (in order to save resources) to ensure that submissions are complete before initiating the extensive evaluation of the data.

Japan

In Japan the production, marketing and use of pesticides are controlled under the Agricultural Chemical Regulation Law, administered by the Ministry of Agriculture, Forestry and Fisheries (hereafter JMAFF).

Under this Law, agrochemicals are defined as 'fungicides, insecticides and other chemicals used for the control of fungi, nematodes, mites, insects, rodents and other animals and plants or viruses that are injurious to crops'. Growth regulators, sprout suppressants and other chemicals that control physiological functions in crops are also covered, as are natural enemies of harmful pests, which are considered to be agrochemicals based on the definition of the word 'control'.

The dossier submitted to JMAFF in support of a registration in Japan is broadly similar to that required in other countries, consisting of data on toxicology, residue chemistry, environmental fate and ecotoxicology data, as well as biological efficacy and phytotoxicity studies. Although JMAFF administers the system, several Ministries are involved in the actual risk assessments for pesticides, with the Environment Agency being responsible for evaluation of crop, soil and water residue data and the Ministry of Health and Welfare (JMHW) being responsible for the evaluation of the toxicological data.

The requirements in terms of the toxicology data are generally in line with harmonised international guidelines and all studies must be GLP-compliant.

However, there is also the specific requirement for a pharmacological study, to investigate acute toxicity reactions in order to identify the symptoms that might arise as a result of acute poisoning incidents and to determine appropriate treatments for such cases.

Another key area where the data requirements in Japan differ from those in other countries is the environmental fate and behaviour package, where specific requirements have been imposed due to special agricultural and environmental conditions. With approximately 50% of Japanese agricultural land used as paddy fields for rice cultivation, and approximately 60% total pesticide use in those rice paddies, the situation is considerably different from those found in Europe or the USA. In addition, more than 70% of drinking water in Japan is obtained from surface water, so a specific requirement for a paddy water residue study conducted using practical field conditions is applied to reflect these special conditions.

The same special conditions are also reflected in the ecotoxicological data package. The basic package is similar to that required in Europe or the USA, but studies on organisms inhabiting paddy fields or paddy sediment and data on estuarine fish may also be required, depending on the nature and use of the product. Also, in addition to the standard non-target arthropod package, there is a specific requirement for data on silkworms, again reflecting the special agricultural conditions in Japan.

Africa

To ensure that pesticides used in the different countries in the Sahel region of West Africa are effective, of suitable quality and a low hazard to man and the environment, the CILSS (Côte d'Ivoire Living Standards Survey) Member States (Burkino Faso, Cape Verde, Chad, Gambia, Guinea Bissau, Mali, Mauritania, Niger and Senegal) in 1992 signed the Common Regulation for the Registration of Pesticides in CILSS Member States. The objective of the Common Regulation is to combine the experience and expertise of Member States with respect to the evaluation and registration of pesticides in order to ensure their rational and judicious use, as well as the protection of human health and the environment.

Future developments

It is clear from the preceding sections that substantial resources are involved in the regulation of pesticides, both on the part of registrants preparing the submission dossiers and the regulatory authorities evaluating the data. It is also clear that the data requirements, risk assessment methods and regulatory procedures may not be very dissimilar from one country to another.

A considerable amount of time is now being spent on various initiatives attempting to harmonise procedures between countries and so to reduce the current duplication of effort in relation to both the evaluation of new active substances and the review programmes that are underway.

There are already several good examples of harmonisation, e.g. that between the EU Member States under Directive 91/414/EEC, where a single regulatory procedure has been established with common data requirements and risk assessment methodologies. With the planned accession of central and eastern European States the harmonisation will be further expanded, with the acceding countries being required to bring their pesticide registration systems in line with those of the Directive.

The USA, Canada and Mexico are committed to share the work involved in pesticide registration, harmonise procedures and reduce trade barriers under the North American Free Trade Association (NAFTA). In pursuit of these objectives, the participating countries are liaising on, *inter alia*, joint reviews of pesticides, developing guidelines and harmonising data requirements. Similar initiatives are being developed between the Australian National registration Authority (NRA) and the Agricultural Compound Unit (ACU) of New Zealand.

Much of this work relating to the harmonisation of procedures and possible reductions in workloads is being pursued under the auspices of the Organisation for Economic Cooperation and Development (OECD). In 1992, the Pesticides Forum (now the Working Group on Pesticides) was established as a meeting of the representatives of the regulatory authorities from the member countries, industry, the European Commission and other organisations such as the World Health Organisation (WHO) and Food and Agriculture Organisation (FAO). The aim of the Working Group is to find common approaches for a range of issues relevant to the risk assessment for pesticides. Initiatives being developed include the possible harmonisation of core data requirements, harmonisation of registration procedures, the exchange of review reports between countries and international collaboration on compiling reviews. These initiatives should give rise to benefits not just for the regulators, where valuable resources currently expended in undertaking (sometimes simultaneous) risk assessments would be saved, but also for the registrants, where harmonised data requirements and risk assessment methods would allow for the acceptance of a single dossier in several different countries.

Implications of the review programmes

Across the globe, several countries have embarked upon a review or re-registration programme designed to re-assess active substances and products originally approved under earlier programmes, to ensure that the risk assessments meet the modern, more stringent safety standards. Roughly, at each stage of the review (notification of intent to support the review, the submission of a complete dossier, and the conclusion of the review following the evaluation of the submission), around half the affected products may no longer be supported.

The third stage of the European review programme is a case in point, with less than half of the 400 active substances included in the programme being supported at the notification stage. It is likely that more of these compounds will fail to be adequately supported when it comes to checking the submissions for completeness and following the evaluation of the data to modern standards. It should also be remembered that even where the active substance is supported, not all of the previously approved uses will necessarily be supported through the review. The 'essential uses' provision in Regulation 451/2000 should help to alleviate the problem in Europe, but only by extending the phase-out period for those uses deemed essential to allow for alternative control measures to be developed.

The loss of so many products as a result of these review programmes could have serious implications for agriculture (Chapter 19), and work needs to begin now to identify the uses that may be affected and new products or alternative methods of control that may solve the problems.

Key points

- Legislative controls over pesticides continue to increase
- Data requirements and risk assessment methods relating to pesticide products are becoming increasingly stringent
- Much work is currently ongoing with regard to the harmonisation of regulatory procedures between countries
- Possible serious implications for agriculture arising from the loss of pesticides as a result of various review programmes need to be addressed

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Chapter 8
Herbicides: Modes of Action and Metabolism

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Introduction

Although some chemical weed control was carried out before the 1940s, the advent of the herbicide industry as we know it today can be traced back to that decade. It was then that two herbicides, 2,4-D and MCPA, were first commercialized. These selective broad-leaf weed herbicides were the beginning of a revolution in agriculture. The availability of chemicals that could control weeds selectively within crops allowed successful cropping to be carried out without the need for intensive use of cultural weed control measures, and a reduced need for manpower to farm land successfully. Between the introduction of these auxin-type herbicides and the mid-1950s, two herbicide groups with other modes of action were introduced: those affecting cell division (mitosis) and the first PS II photosynthetic inhibitors (ureas). Most other modes of action that we use today were introduced subsequently, between 1955 and 1975. Since 1980 only three new modes of action have been commercialised: inhibition of acetolactate synthase (the ALS inhibitors), inhibition of glutamine synthase and inhibition of 4-hydroxyphenylpyruvate dioxygenase (the 4-HPPD inhibitors). The last of these was introduced in the mid-1990s.

The current number of herbicide targets, between 15 and 20, is remarkably low considering the thousands of reactions taking place in plant cells. This has had a severe impact on the industry, not least in respect to the growing problem of herbicide resistance. The occurrence of weed populations displaying multiple resistance to herbicides means that in some weed control situations, new modes of action are needed. Herbicide target sites exploited to date are shown in Table 8.1. Herbicide discovery should ideally satisfy the following criteria. The herbicide should

(1) be highly selective to plants and non-toxic to other organisms
(2) act quickly and effectively at low doses,
(3) rapidly degrade in the environment, and
(4) be cheap to produce and purchase.

However, few if any available products satisfy all of these criteria. In order to show a high degree of plant selectivity, target sites unique to plants should be utilized, as this should offer little or no toxicity to non-target (non-plant) organisms. These include, for example, targeting the inhibition of photosynthesis

Table 8.1 Classification of herbicide families according to mode of action*

Group	Mode of action	Chemical family	WSSA† group
A	Inhibition of acetyl-CoA carboxylase (ACCase)	Aryloxyphenoxypropionates Cyclohexanediones	1
B	Inhibition of acetolactate synthase (ALS)	Sulfonylureas Imidazolinones Triazolopyrimidines Pyrimidinylthiobenzoates	2
C_1	Inhibition of photosynthesis at photosystem II	Triazines Triazinones Uracils Pyridazinones Phenylcarbamates	5
C_2	Inhibition of photosynthesis at photosystem II	Phenylureas Amides	7
C_3	Inhibition of photosynthesis at photosystem II	Hydroxybenzonitriles Benzothiadiazole Phenylpyridazine	6
D	Photosystem I electron diversion	Bipyridyliums	22
E	Inhibition of protoporphyrinogen oxidase (Protox)	Diphenyl ethers *N*-Phenylphthalimides Thiadiazoles Oxadiazoles Triazolinones	14
F_1	Bleaching: inhibition of carotenoid biosynthesis at the phytoene desaturase (PDS) step	Pyridazinones Nicotinanilides Others	12
F_2	Bleaching: inhibition of 4-hydroxyphenylpyruvate dioxygenase (4-HPPD)	Triketones Isoxazoles Pyrazoles	28
F_3	Bleaching: inhibition of carotenoid biosynthesis (unknown target)	Triazoles Isoxazolidinones Phenylureas	11 13 11
G	Inhibition of EPSP synthase	Glycines	9
H	Inhibition of glutamine synthetase	Phosphinic acids	10
I	Inhibition of dihydropteroate synthase (DHP)	Carbamates	18
K_1	Microtubule assembly inhibition	Dinitroanilines Phosphoroamidates Pyridazines Benzoic acids	3

Contd.

Table 8.1 *Contd.*

Group	Mode of action	Chemical family	WSSA† group
K_2	Inhibition of mitosis	Carbamates Benzyl ethers	23 27
K_3	Inhibition of cell division	Chloroacetamides Carbamates Acetamides Benzamides Oxyacetamides	15
L	Inhibition of cell wall (cellulose) biosynthesis	Nitriles Benzamides	20 21
M	Uncoupling (membrane disruption)	Dinitrophenols	24
N	Inhibition of lipid biosynthesis – not ACCase inhibition	Thiocarbamates Phosphorodithioates Benzofurans Chlorocarbonic acids	8 26
O	Synthetic auxins	Phenoxycarboxylic acids Benzoic acid Pyridine carboxylic acids Quinoline carboxylic acids Others	4
P	Inhibition of indoleacetic acid action	Phthalamate Semicarbazone	19
Z	Unknown	Arylaminopropionic acids Organoarsenicals Others	25 17 8, 27

* From *Herbicide Resistance Action Committee Classification of Herbicides According to Mode of Action* (1998). See also http://www.plantprotection.org/HRAC/MOA.html
† WSSA, Weed Science Society of America.

and pigment, amino acid and lipid biosynthesis in the chloroplast. Non-chloroplast target sites that are unique to plants include cell wall biosynthesis and plant hormone systems.

In addition to the 15–20 targets already utilized, a further 33 target enzymes have been identified but not yet translated into commercial herbicides, and another 26 additional receptors and enzymes have been patented as potential herbicide targets. It is likely that by 2010 some of these will be exploited as new commercial herbicides appearing in the marketplace. Our increasing understanding of plant biochemistry and physiology means other target sites are likely to be identified and exploited in herbicide development in the future.

Selectivity of herbicides between crop and weed species may, in some cases, reflect differences in target site chemistry and structure. However, in the majority of cases it is the difference in herbicide metabolism that ensures the crop is undamaged whilst weeds are successfully killed. Differences both in metabolic pathways and in the rate at which these pathways operate are encountered, and in some cases these differences can be enhanced by the use of herbicide safeners. In addition, some degree of metabolism may be necessary for the bioactivation of certain herbicides. Successful herbicide metabolism must be fast, to remove the herbicide before it significantly affects the target site, and it must give rise to less or non-phytotoxic metabolites. In general, herbicide metabolism can be divided into three distinct phases. Firstly, a range of primary enzymic reactions can render the herbicide more soluble, less toxic and more suited to further metabolism. Secondly, a variety of conjugation reactions to, for example, amino acids and sugars can take place, further detoxifying and increasing solubility. Finally, herbicide metabolites can be compartmentalised either in the cell vacuole or in the cell wall. This last step creates a spatial separation between the herbicide metabolite and the target site. In addition, it also removes these metabolites from causing a general interference with plant metabolism. They may be further metabolized, stored or excreted outside the cell.

Since 1990, production of herbicide-resistant crops by the use of transgenic techniques has allowed the use in crop situations of herbicides that would usually cause crop damage or death. By introducing herbicide-resistant target sites into crops, absolute selectivity can be obtained. This has allowed the use of the total herbicides glyphosate and glufosinate in crops, and of sulfonylureas, bromoxynil, protox inhibitors and imidazolinones in crops for which they were previously unsuited. Undoubtedly these developments simplify weed control in these cases, but care must be exercised that usage of such crops does not result in a decline in research and development of traditional and new herbicide target sites, or encourage the use of extensive monoculture and use of single herbicide types. In addition, environmental, ethical and financial considerations need to be addressed before such crops can be allowed to pass beyond the research stage in Europe.

Modes of herbicide action

Interaction with photosynthesis

Photosynthesis is the process by which carbon dioxide is converted to carbohydrate, utilising solar energy (Equation 8.1). It is carried out by all organisms possessing the photosynthetic pigment chlorophyll. All plants possess chlorophyll, and hence rely on photosynthesis in order to survive, grow and reproduce. Any substance that can inhibit photosynthesis, or reduce its efficiency, will therefore have a major effect on plant survival.

$$CO_2 + H_2O \xrightarrow{\text{Light}} (CH_2O)_n + O_2 \qquad (8.1)$$

The light-absorbing pigments (chlorophyll and carotenoids) are found in lipoprotein thylakoid membranes within chloroplasts, which are specialised photosynthetic organelles within plant cells. Leaf cells may contain hundreds of chloroplasts. Photosynthesis can be divided into a complex series of light (light-requiring) and dark (non-light-requiring) reactions. The light reactions involve absorption of light energy by the photosynthetic pigments and the subsequent generation of adenosine 5′-triphosphate (ATP) and reducing power, as nicotinamide adenine dinucleotide phosphate (NADPH). A photon of light is absorbed by the light-harvesting complex and the excitation energy is transferred to the reaction centre chlorophyll, where an electron is moved from a low- to a high-energy state. This electron then passes through a series of electron carriers to a relatively low-energy state, and the released energy is utilized in the production of ATP and reductant.

Two photosystems are present in photosynthesis. Photosystem II (PS II; Fig. 8.1) replaces the excited electron with one from water, resulting in the production of oxygen (O_2) and the excited electron is passed to photosystem I via plastoquinone. Hence, PS II can be referred to as water-plastoquinone oxidoreductase. Photosystem I (PS I; Fig. 8.2) replaces the excited electron with one from plastoquinone (via plastocyanin) and the excited electron is passed, via a series of electron carriers, to $NADP^+$ (to produce NADPH – reducing power) via ferredoxin. Hence, PS I can be described as plastocyanin–ferredoxin oxidoreductase. The dark (non-light-requiring) phase of photosynthesis involves the utilisation of energy (as ATP) and reductant (as NADPH) in the fixing of carbon dioxide (CO_2) by ribulose 1,5-bisphosphate carboxylase and the subsequent generation of carbohydrates by a process termed the photosynthetic carbon reduction, or Calvin cycle.

Herbicides that affect photosynthesis do this either by disrupting or diverting electron flow within the light reactions or by affecting the biosynthesis of photosynthetic pigments. If electron transfer is blocked the excited 'singlet-state'

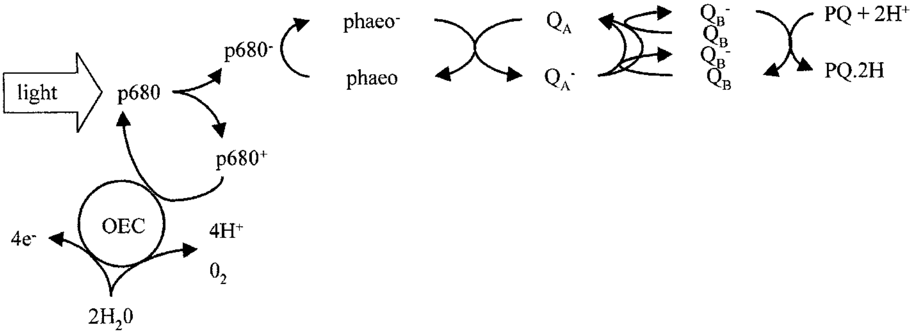


Fig. 8.1 Functional model of photosystem II. p680, PS II reaction centre; phaeo, phaeophytin a; Q_A and Q_B, quinones; PQ, mobile plastoquinone pool; OEC, oxygen evolving complex.

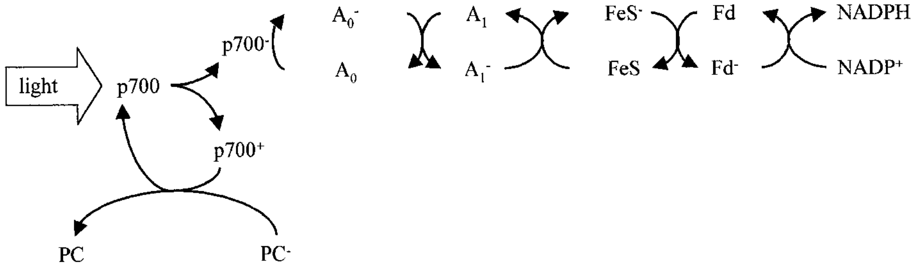


Fig. 8.2 Functional model of photosystem I. p700, PS I reaction centre; A_0 and A_1, electron acceptors/donors; FeS, iron–sulphur centres; Fd, ferredoxin; the final electron acceptor is $NADP^+$; PC, plastocyanin (the electron donor to $p700^+$).

chlorophyll (^{1}Chl) may release its energy by fluorescence. In addition, ^{1}Chl can be transformed to the longer-lived triplet-state chlorophyll (^{3}Chl). This can cause direct and irreversible damage to membrane lipids (i.e. lipid peroxidation) and can also excite O_2 to a singlet state ($^1O_2$). This is an extremely reactive species that can cause damage to many molecules and also give rise to other damaging active oxygen species (AOS). These include superoxide and peroxide anions, and hydrogen peroxide. They are all highly reactive, and cause damage to many biological molecules, including unsaturated fatty acids found in the thylakoid membrane. Although both ^{3}Chl and $^1O_2$ are produced to some extent during normal photosynthesis, they are quenched by protective carotenoids and other antioxidants before they can cause extensive cellular damage. All organisms have a series of enzymes specifically designed to deal with AOS. These include superoxide dismutase (SOD), aspartate peroxidase, dehydroascorbate reductase and glutathione reductase. When herbicides interact with the thylakoid, the resultant ^{3}Chl and $^1O_2$ are produced in amounts too great for the protective quenching mechanisms, and hence give rise to AOS that ultimately lead to cell death. It is this process, rather than starvation due to cessation of photosynthetic carbohydrate production, which causes plant death.

Herbicide families that block electron transfer at PS II include triazines, triazinones, uracils, nitriles, benzothiadiazoles, phenylpyridazines, ureas and amides. Examples are given in Table 8.2. These all act by competitively binding to the D1 protein in PS II, preventing electron transfer to Q_B (a quinone). However, they bind at different sites on this protein. Thus, resistance to triazine herbicides due to modification of the D_1 protein at aa264 confers cross-resistance to the triazinones and uracils, but not the other classes of PS II herbicide. This would suggest that although all bind to the D_1 protein there are at least three different binding sites present, as the PS II herbicides can be divided into three groups possessing intragroup cross resistance. In addition to the mode of action outlined above, the active photosystems require continuous provision of β-carotene in order for D_1 protein turnover to occur. Inhibition of carotenoid biosynthesis

Table 8.2 Examples of herbicides that inhibit photosynthesis at PS II

Chemical family	Examples
Triazines	atrazine, propazine, simazine, terbumeton
Triazinones	hexazinone, metamitron, metribuzin
Uracils (Pyrimidines)	bromacil, lenacil, terbacil
Pyridazinones	pyrazon
Phenylcarbamates	desmedipham, phenmedipham
Phenylureas	chlorotoluron, diuron, isoproturon, metoxuron
Amides	propanil
Nitriles	bromoxynil, ioxynil
Benzothiadiazoles	bentazon
Phenylpyridazine	pyridate

(covered below) therefore also disrupts D_1 protein turnover and hence indirectly causes photosynthetic inhibition.

Herbicides that disrupt electron flow at PS I are the bipyridyliums, paraquat and diquat. Rather than inhibiting electron flow, they 'hijack' electrons at the PS I reaction centre and become free radicals themselves. Their activity is greatly enhanced by light, and these herbicide radicals subsequently reduce molecular O_2 to produce AOS. It is these that cause cell damage and ultimately plant death.

Inhibition of pigment biosynthesis

Chlorophyll biosynthesis inhibitors

Both chlorophyll and carotenoids are integral to light harvesting and hence photosynthesis. In addition, carotenoids play an important role in protecting chlorophyll from destruction by AOS and in the cycling of the D_1 protein in PS II. Chlorophyll has a dual role as a light-harvesting pigment and as an integral part of the photosynthetic reaction centres where electrons are moved from low to higher energy. Biosynthesis of chlorophyll (Fig. 8.3) begins with the formation of δ-aminolaevulinic acid (ALA) and its subsequent conversion to porphobilinogen (PBG). ALA is synthesized by ALA synthase (EC 2.3.1.37) from glycine and succinyl-CoA. This initial step is also essential for the biosynthesis of phytochromes, cytochromes, peroxidases and catalases.

Herbicides that inhibit chlorophyll biosynthesis act at the enzyme protoporphyrinogen oxidase (PPO; Protox), a membrane-bound protein found in the chloroplast, and are referred to as either PPO or Protox inhibitors (see Table 8.3 for examples). Protoporphyrinogen oxidase (EC 1.3.3.4) converts protoporphyrinogen IX (PPG IX) to protoporphyrin IX (PP IX), an integral step in the formation of chlorophyll and other metalloporphyrins (the iron-containing haems). Inhibition of this enzyme leads to the build-up of PPG IX in the chloroplast, and leakage into the cytoplasm occurs where enzymic oxidation

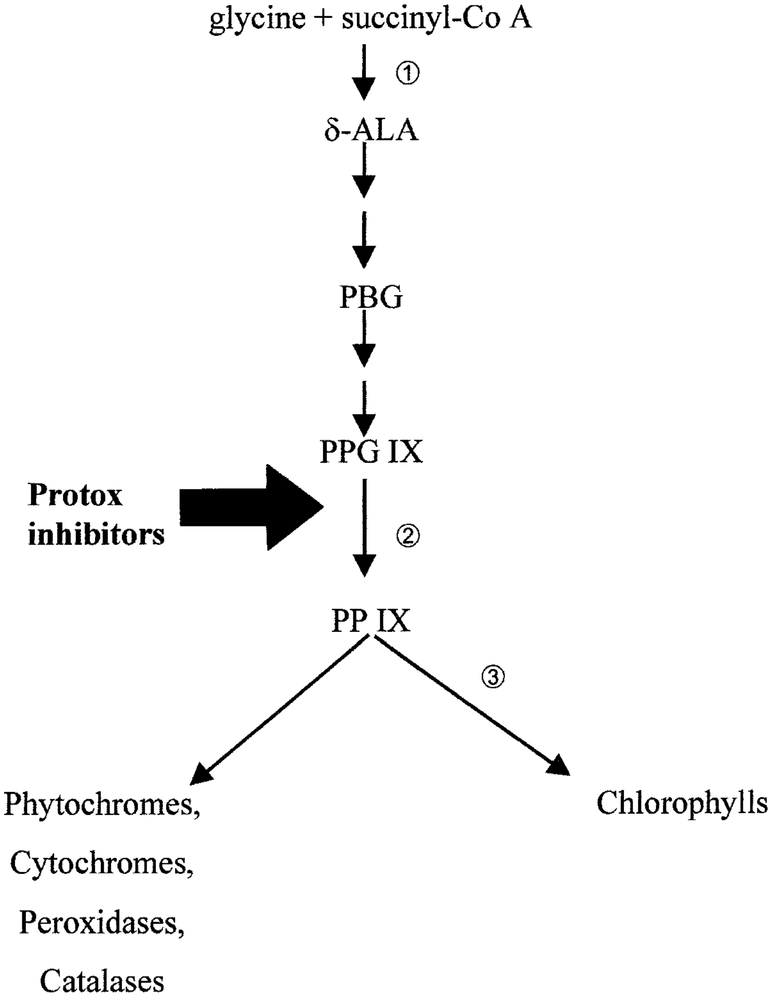


Fig. 8.3 Chlorophyll biosynthesis, indicating the point at which herbicides act. For abbreviations, see text. ① = ALA synthase; ② = protoporphyrinogen oxidase; ③ = Mg chelatase.

converts it to PP IX. This molecule reacts with light and O_2 to give rise to singlet oxygen, and AOS damage subsequently occurs, leading to plant death. The reason that this takes place in the cytoplasm but not in the chloroplast is because of the absence of a cytoplasmic enzyme capable of placing a magnesium ion in PP IX to form MgPP IX. In the chloroplast this is the next step in chlorophyll biosynthesis, catalysed by Mg chelatase, and the tightly regulated biosynthetic pathway avoids any build-up of PP IX. This explains the apparent enigma of why blocking PP IX formation with Protox inhibitors is seen to cause a rise in PP IX concentrations within treated plants. This hypothesis does rely on the cyto-

Table 8.3 Examples of herbicides that inhibit protoporphyrinogen oxidase (Protox inhibitors)

Chemical family	Examples
Diphenyl ethers	aclonifen, bifenox, fomesafen, oxyfluorfen
N-Phenylphthalimides	flumioxazin, flumiclorac-pentyl
Thiadiazoles	fluthiacet-methyl, thidiazimin
Oxadizole	oxadiazon
Triazolinones	carfentrazone, sulfentrazone

plasmic enzyme that catalyses the conversion PPG IX to PP IX being much less sensitive to the herbicides than the chloroplastic enzyme Protox.

Carotenoid biosynthesis inhibitors

Carotenoids are a large family of pigments that are also involved in light harvesting during photosynthesis, cycling of the D_1 protein at PS II reaction centres and protection of chlorophyll from attack by AOS. The last of these roles is accomplished by the ability of carotenoids to quench both triplet-state chlorophyll and singlet oxygen. In the absence of sufficient levels of carotenoids these species would lead to rapid free-radical attack and lipid peroxidation. Carotenoids are synthesised via the mevalonic acid pathway in the chloroplast, and this is the site of action of a number of herbicides (Fig. 8.4 and Table 8.4).

The mevalonic acid pathway involves the condensation of isopentenyl pyrophosphate (a five-carbon compound; IPP) units to produce many molecules of biological importance. Following geranylgeranyl pyrophosphate (20-carbon; GGPP) biosynthesis from four IPP units, 15-*cis*-phytoene (40-carbon) is formed by condensation of two GGPP molecules. This is a true carotenoid precursor and is converted to all-*trans*-lycopene by a series of desaturase-catalysed reactions. β-Carotene and lutein (major carotenoids) are subsequently formed by cyclisation and ring hydroxylation. Inhibition of this pathway at the early stages (up to the formation of GGPP) would result in the cessation of synthesis of many biologically important molecules, including chlorophyll. However, if inhibition takes place at any step between GGPP and carotenoids, then this would specifically block carotenoid biosynthesis. It is here that the herbicides shown in Table 8.4 act.

Carotenoid biosynthesis involves synthases, desaturases and cyclases. The most important site of action of carotenoid biosynthesis herbicides appears to be at the desaturase steps (phytoene desaturase and/or ξ-carotene desaturase). Diflufenican, fluridone and difunon lead to accumulation of phytoene *in vivo*, suggesting inhibition of phytoene desaturase. Other herbicides (including diclormate and methoxyphenone) lead to the accumulation of phytoene, phytofluene and ξ-carotene, suggesting inhibition of ξ-carotene desaturase or both the desaturases. Research has suggested that these herbicides may not be entirely

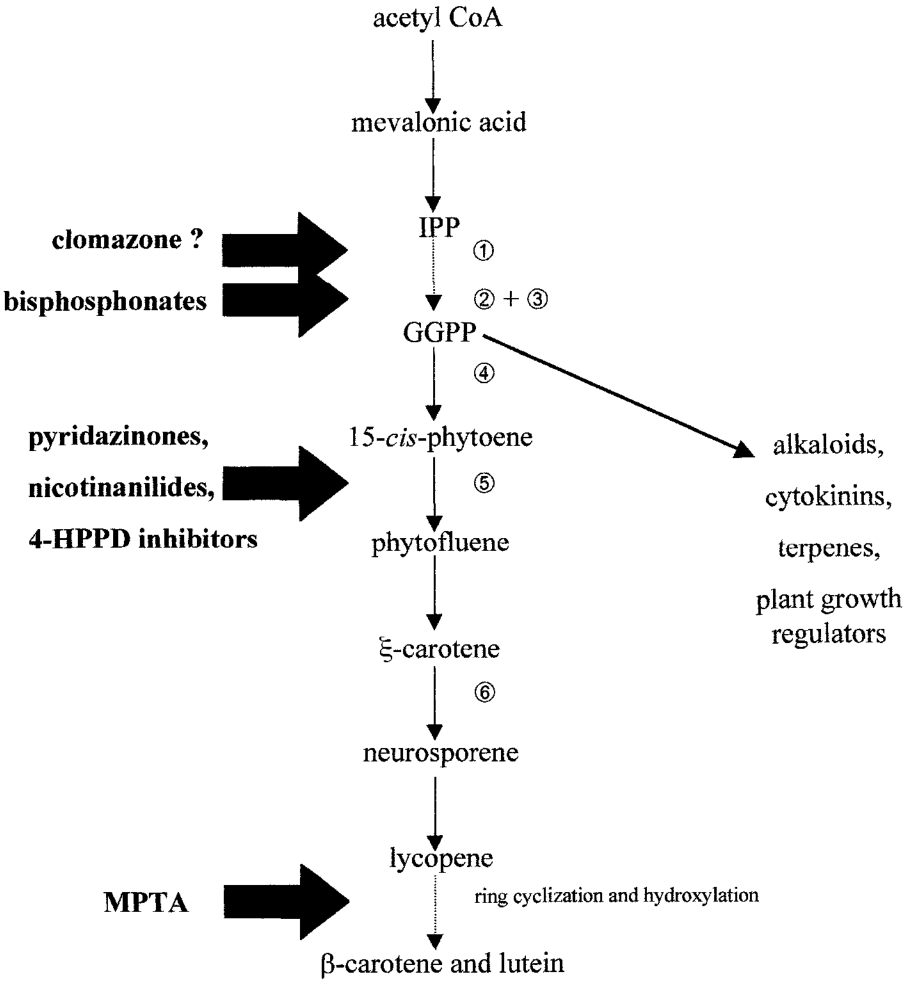


Fig. 8.4 Carotenoid biosynthesis, indicating the points at which herbicides act. For abbreviations, see text. ① = IPP isomerase; ② = farnesyl PP synthase; ③ = GGPP synthase; ④ = phytoene synthase; ⑤ = phytoene desaturase; ⑥ = ξ-carotene desaturase.

specific to one desaturase, but may inhibit more than one step. That the pyridazinones have been implicated in inhibiting desaturase reactions in both lipid and carotenoid biosynthesis further supports this theory.

The 4-HPPD inhibitors are a relatively new group of herbicides that indirectly inhibit phytoene desaturase by inhibiting synthesis of plastoquinone (PQ), an essential cofactor for the desaturase. 4-Hydroxyphenylpyruvate dioxygenase (4-HPPD; EC 1.13.11.27) is an enzyme that is involved in the metabolic pathway for the synthesis of plastoquinone from tyrosine. This takes place in the chloroplast and is the same pathway that leads to biosynthesis of α-tocopherol, a powerful

Table 8.4 Inhibitors of carotenoid biosynthesis (bleaching herbicides)

Mode of action	Chemical family	Examples
Inhibition of phytoene desaturase	Pyridazinones	norflurazon
	Nicotinanilides	diflufenican
	Others	fluridone, flurochloridone, flurtamone
Inhibition of 4-HPPD	Triketones	sulcotrione
	Isoxazoles	isoxaflutole
	Pyrazoles	pyrazolynate, pyrazoxyfen
Unknown site of action	Triazoles	amitrole
	Isoxazolidinones	clomazone
	Ureas	fluometuron

antioxidant. PQ is not only an essential cofactor for phytoene desaturase but is also an essential carrier of protons and electrons in the thylakoid membrane. Hence, 4-HPPD inhibitors not only indirectly inhibit phytoene desaturase, but may also disrupt thylakoid membrane function and reduce protection from damage by AOS.

Lycopene cyclase, involved in the later stages of carotenoid biosynthesis, has been identified as the site of action of the *N*,*N*-diethylamines *N*,*N*-diethyl-*N*-(2-undecynyl)amine (NDUA), 2-(4-chlorophenylthio)triethylamine (CPTA) and 2-(4-methylphenoxy)triethylamine (MPTA). It has also been shown that these compounds subsequently inhibit photosynthesis at PS II by interfering with the turnover of the D_1 protein, which requires a constant β-carotene source. The bisphosphonates (e.g. CGA 103586) have recently been implicated in inhibition of either the farnesyl pyrophosphate or GGPP synthase. Inhibition of either enzyme would result in cessation of synthesis of GGPP, a precursor of both chlorophyll and the carotenoids. However, the potential of these compounds as herbicides is seriously hampered by their poor foliar uptake by plants.

Other herbicides implicated in affecting carotenoid biosynthesis include the isoxazolidinones and triazoles. Sites of action of these herbicides have not been satisfactorily identified. The urea fluometuron, a PS II photosynthetic inhibitor, appears to have a bleaching effect on treated tissue, suggesting a dual mode of action.

Regardless of how carotenoid biosynthesis is inhibited, the decline in the carotenoid pool indirectly leads to cell death. Carotenoids play an essential role in preventing oxidative damage to chlorophyll, and hence peroxidative lipid (membrane) damage. In addition, recent research demonstrating an absolute need for β-carotene in PS II also implies that an inhibition of photosynthesis would occur with the inhibition of the synthesis of these compounds. It is a combination of these factors that leads to cell disruption and death. Successful herbicidal inhibition of carotenoid biosynthesis needs to be carried out during development of new tissue. Mature tissue already contains carotenoid levels that can act as protectants for chlorophyll. Norflurazon, flurochloridone and diflufenican are used as pre-emergence herbicides. Germinating weeds lack carotenoids and hence photoprotection. This in turn leads to lipid peroxidation following seedling emergence, and ultimately plant death.

Inhibition of lipid biosynthesis

Lipids are essential components of plant life. They are major seed-storage components, they can regulate enzyme activity and they are also major components of all cellular membranes. Their role in plant membranes is both structural and biochemical, and the presence of different lipids within a particular membrane can dictate the role of a particular membrane as well as reflecting environmental conditions in which the plant is found. The ability of the thylakoid membrane to allow movement of protons, electrons and their carriers is a result of the presence of the unsaturated fatty acid α-linolenic acid (18 carbons with three double bonds, 18:3) in the lipids present, along with *trans*-Δ^3-hexadecanoic acid and linoleic acid (18:2). These unsaturated fatty acids are thought to give fluidity to membranes. Membrane lipids also play an integral role in electron transport systems in the inner membrane of mitochondria and therefore play a vital role in respiration as well as photosynthesis.

The major component of most lipids is the fatty acid. Approximately 200 fatty acids are found in plants; these may be saturated or unsaturated, and may contain acetylenic bonds, epoxy, hydroxy and keto groups, and cyclopropene or cyclopentene rings. However the majority of these features only occur in a few species. The 'major' fatty acids are those that are found in abundance throughout the plant kingdom in most aryl lipids. These are the saturated fatty acids – lauric (12:0), myristic (14:0), palmitic (16:0) and stearic (18:0) – and the unsaturated fatty acids – oleic (18:1), linoleic (18:2) and α-linolenic (18:3). Fatty acid biosynthesis is important in providing new membrane for plant growth and development and also for replacing lipid damaged by AOS. The first committed step in fatty acid synthesis is carried out by the enzyme acetyl-CoA carboxylase (ACCase; EC 6.4.1.2). This enzyme catalyses the formation of malonyl-CoA from acetyl-CoA and a one-carbon unit provided by a biotin cofactor functioning as a CO_2 carrier. Following this step, two carbon units derived from malonyl-CoA are condensed together to form fatty acids of progressively longer chain length. This is carried out by a multienzyme complex termed fatty acid synthase. Following this synthesis, usually up to palmitic acid (16:0), other enzyme systems further elongate the chain to form very long-chain saturated fatty acids, or elongate and desaturate to form very long-chain mono- and poly-unsaturated fatty acids. Figure 8.5 summarizes lipid (fatty acid) biosynthesis and indicates the points at which herbicidal interaction with this process occurs.

ACCase is the enzyme catalysing the first committed step in fatty acid biosynthesis. It is at this point that the selective graminicides aryloxyphenoxy-

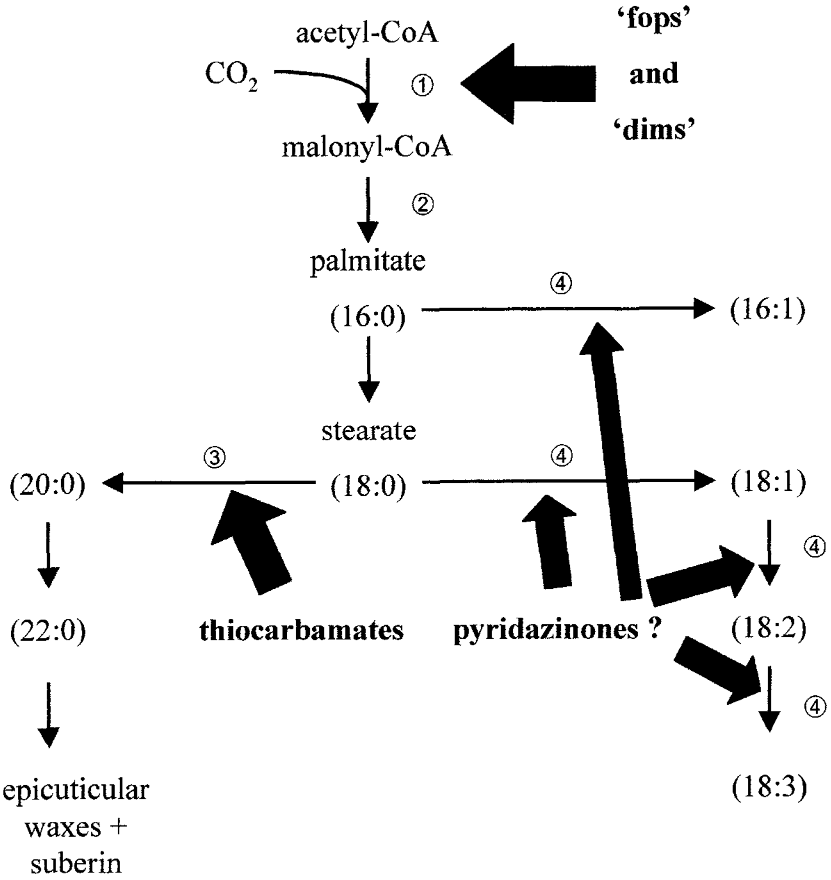


Fig. 8.5 Fatty acid (lipid) biosynthesis, indicating the points at which herbicides act. ① = ACCase; ② = fatty acid synthetase; ③ = elongases; ④ = desaturases.

propionates ('fops') and cyclohexanediones ('dims') act. These compounds are used extensively in the post-emergence control of grass weeds; examples of these ACCase inhibitors are given in Table 8.5. ACCase is a high-molecular-weight multifunctional protein with three distinct functional regions. These are biotin carboxylase, biotin carboxyl carrier protein (BCCP) and BCCP:acetyl-CoA transcarboxylase. A carboxyl group is donated from a bicarbonate anion and carboxybiotin is formed by biotin carboxylase. This step requires ATP hydrolysis. Carboxybiotin is then attached to BCCP and functions as a CO_2 donor to form malonyl-CoA by the action of BCCP:acetyl-Co A transcarboxylase.

Experiments have revealed that the transcarboxylase reaction appears to be the site of inhibition for both 'fops' and 'dims' rather than the reaction of the biotin carboxylase. Inhibition is both rapid and concentration-dependent. Both haloxyfop and tralkoxydim (at 1 μM) will inhibit ACCase activity *in vitro* by 50%

Table 8.5 Examples of herbicides that inhibit ACCase

Chemical family	Examples
Aryloxyphenoxypropionates ('fops')	clodinafop-propargyl, diclofop-methyl, fenoxaprop-P-ethyl, quizalofop-P-ethyl
Cyclohexanediones ('dims')	alloxydim, clethodim, cycloxydim, sethoxydim

in just 20 min. The free acid 'fops' are the herbicidally active forms – 'fops' are formulated as esters (ethyl, methyl, propargyl, etc.) to aid in herbicide uptake and transport into the cell, and the free acid is released by the action of cytoplasmic esterases. Only the *R* enantiomeric forms are herbicidally active and recent herbicide formulations containing only this form have been commercialised. Original formulations contained both the active *R* and inactive *S* enantiomers.

Activity of ACCase inhibitors is greatly enhanced when the grasses are growing actively. ACCase is present in rapidly dividing cells and in active chloroplasts, and visible symptoms of ACCase inhibitor treatment are mostly observed in the meristematic regions. Here, irreversible disruption of membrane synthesis, especially of the thylakoid, causes metabolic alterations. Growth ceases within two days in this region and chlorosis appears, especially in young leaves where chloroplast disruption is most marked. Secondary effects of herbicide action include decreases in long-chain fatty acids in the chloroplast, which are replaced by 16:0 or shorter ones. Mitosis and DNA synthesis are also inhibited. Plant death occurs two to three weeks after application. Symptoms are similar for both 'fops' and 'dims', although slower rates of penetration into leaves by 'dims' often result in slower responses to treatment.

Selectivity of 'fops' and 'dims' appears to reside in ACCase insensitivity to these herbicides, as well as in increased metabolism, in tolerant species. That 'fops' and 'dims' are selective graminicides, active against grasses without harming many broad-leaved species, appears to be due to an alternative ACCase found in dicotyledons. Grasses contain one ACCase, termed 'prokaryote ACCase' because of its resemblance to the enzyme found in prokaryotic systems. It is sensitive to 'fops' and 'dims'. Dicotyledons contain this ACCase and, in addition, a second ACCase termed 'eukaryote ACCase'. This enzyme is insensitive to 'fops' and 'dims' and hence allows lipid biosynthesis to continue after herbicide treatment. Interestingly, recent research with a broad-leaved plant (*Erodium moschatum*) that lacked the eukaryote ACCase also demonstrated that a number of such plants were sensitive to ACCase inhibitor herbicides. This further supports the theory that alternative ACCase plays a role in selectivity of these graminicides in broad-leaved crops. In cereal crops, which do not possess this alternative ACCase, selectivity appears to be due to enhanced metabolism of the herbicide in the crop.

The thiocarbamates are a group of herbicides that inhibit lipid biosynthesis at a specific elongase bound to the endoplasmic reticulum. Examples of these and other non-ACCase lipid biosynthesis inhibitors are given in Table 8.6. Inhibition of this elongase prevents synthesis of very long-chain fatty acids (VLCFAs) and therefore biosynthesis of suberin and cuticular wax. Following treatment, a decrease in the amount of cuticular wax and a change in its composition, to contain less VLCFAs and more short-chain fatty acids, are noted. This results in dehydration of the plant and also an increased chance of pathogen attack.

Table 8.6 Examples of herbicides that inhibit non-ACCase lipid biosynthesis

Chemical family	Examples
Thiocarbamates	butylate, EPTC, molinate, triallate
Phosphorodithioates	bensulide
Benzofurans	ethofumesate
Chlorocarbonic acids	TCA, dalapon

Treatment with thiocarbamates also results in increased uptake of soil-applied herbicides as a result of increased transpiration. Inhibition of the elongase appears to take place in young tissue and pre-emergence treatment results in seedling death once fatty acid reserves from the seed are used up. Bioactivation appears to take place in susceptible species by means of sulphoxidation to a more phytotoxic product. In tolerant species this is then conjugated to glutathione as an important detoxification step. Crop selectivity of thiocarbamates appears to be due to metabolism and depth of penetration of the herbicide in the soil (as these compounds require incorporation). The high volatility of the thiocarbamates may also aid in their selectivity, allowing the chemical to vaporise before the crop has used up its seed fatty reserves.

Although classified as carotenoid biosynthesis inhibitors, the pyridazinones have also been found to inhibit lipid biosynthesis. The sites of action appear to be various desaturases that catalyse the formation of mono- and poly-unsaturated fatty acids. This is perhaps not surprising, as it is the desaturase step that these compounds inhibit during carotenoid biosynthesis.

Inhibition of amino acid biosynthesis

Amino acids are components of proteins and as such are necessary for both enzymic and structural functions. Unlike animals, plants can synthesise all the amino acids they require. Any chemical that can inhibit synthesis of these amino acids will not only kill the plant, but is also unlikely to have an effect on animals, as they do not possess the metabolic pathways being inhibited. Herbicides acting at these pathways have been in use since the early 1970s and are widely used in both total and selective weed control programmes. In recent years the genetic modification of crops to be resistant to certain inhibitors of amino acid biosynthesis has meant renewed interest and focus on this mode of action.

ALS inhibitors

The ALS inhibitors are a number of structurally diverse herbicides that act by inhibiting the enzyme acetolactate synthase (ALS; EC 4.1.3.18), also referred to as acetohydroxy acid synthase (AHAS). Examples of these herbicides are given in Table 8.7. ALS is a key enzyme in the biosynthesis of the branched-chain amino acids isoleucine, leucine and valine (Fig. 8.6). ALS is located in the chloroplast, although the gene encoding it is nuclear. It catalyses the condensation reaction of two pyruvate molecules to form 2-acetolactate, which is a precursor of valine and leucine. In addition, the same enzyme can catalyse the condensation of pyruvate and 2-ketobutyrate to form 2-acetohydroxybutyrate, a precursor of isoleucine. It appears that the herbicides of this class do not compete with substrates at the active site of the enzyme, but at a ubiquinone site. It is unusual that ALS should have such a site, as it does not use ubiquinone as a cofactor. It has been postulated that as ALS shows a high degree of amino acid sequence homology with pyruvate oxidase (which does use ubiquinone as a cofactor), the ALS ubiquinone site is a vestigial or 'residual' binding site for a cofactor that is no longer required.

Table 8.7 Examples of herbicides that inhibit ALS

Chemical family	Examples
Sulfonylureas	chlorimuron-ethyl, chlorsulfuron, halosulfuron-methyl, primisulfuron-methyl
Imidazolinones	imazameth, imazamethabenz-methyl, imazapyr, imazethapyr
Triazolopyrimidines	cloransulam-methyl, diclosulam, flumetsulam, metosulam
Pyrimidinylthiobenzoates	bispyribac, pyribenzoxim, pyrithiobac-Na, pyriminobac-methyl

ALS inhibitors very rapidly inhibit cell division in susceptible weeds. This is apparently because of a direct effect of inhibition of amino acid biosynthesis, as inclusion of isoleucine or valine in growth media will counteract these ALS symptoms. Although growth inhibition occurs rapidly, plants can take days to show physical symptoms and between ten days and two weeks to die. This may be because amino acid pools within the plant support metabolism (though not cell division) and plant death only occurs once these pools have fallen below a critical concentration.

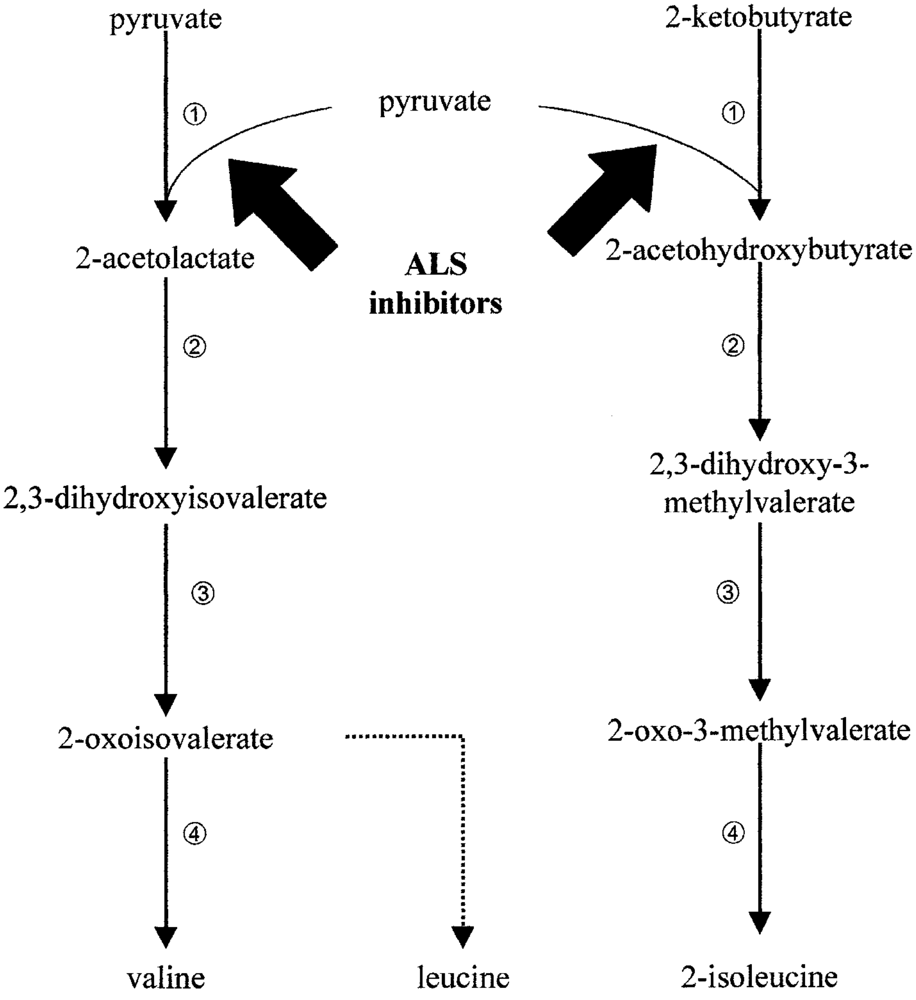


Fig. 8.6 Branched-chain amino acid biosynthesis, indicating the point at which herbicides act. ① = acetolactate synthase; ② = acetohydroxy acid reductoisomerase; ③ = dihydroxy acid dehydratase; ④ = aminotransferase.

Selectivity of these compounds appears to reside in a crop's ability to metabolise the herbicides very rapidly to non-toxic metabolites. In the case of wheat, imazamethabenz is metabolised by ring-methyl hydroxylation (to a herbicidally inactive product) followed by glycosylation. In wild oats, which is sensitive to this herbicide, its metabolism to a phytotoxic acid, by esterases, is observed. This type of metabolism might also explain sensitivity of sugar beet to ALS inhibitors, if this species lacks appropriate metabolising enzymes found in tolerant crops.

Histidine biosynthesis inhibitors

The herbicide amitrole, previously discussed as an inhibitor of carotenoid biosynthesis, also appears to inhibit synthesis of histidine in plants. The enzyme inhibited appears to be IGP dehydratase, which is involved in the metabolic pathway converting imidazole glycerol phosphate (IGP) to histidine. Treatment with amitrole causes a build-up of IGP and imidazole glycerol (IG), suggesting inhibition at the dehydratase step. It should be noted that addition of histidine to growth media does not counteract the symptoms of phytotoxicity, so that although this might be an important mechanism of action, it may not be the only site at which amitrole acts.

Glutamine synthetase inhibitors

Glutamine synthetase (GS; EC 6.3.1.2) is a major enzyme in nitrogen metabolism that assimilates both ammonia produced by nitrate reductase and ammonia produced by photorespiration and deamination reactions. The enzyme is found in both the cytoplasm and the chloroplast. In green tissue the chloroplast form predominates. The enzyme is responsible for the synthesis of the amino acid L-glutamine from L-glutamate, utilising ATP and ammonia (Fig. 8.7).

Glufosinate-ammonium is a non-selective, post-emergence herbicide introduced in 1981 for the total control of vegetation. The mode of action of this herbicide is the inhibition of glutamine synthetase. Glufosinate-ammonium is a structural analogue of glutamic acid (Fig. 8.8) and, as such, inhibits the enzyme at its active site. Glufosinate appears to form an enzyme–glufosinate–phosphate complex that results in an irreversible inhibition of the enzyme. Plant death usually results within five days. This rapidity may be due to an increase in intracellular ammonia, which would uncouple electron flow from proton transport within the thylakoid. The result would be the inhibition of photosynthetic energy production. This is supported by observations that phytotoxicity is observed only if the treated plant is exposed to light. It would appear likely that other membrane transport processes would also be disrupted by increased ammonia concentrations, which would cause disruption of a variety of cellular processes and lead to cell death.

During the 1990s production of crops genetically modified to be resistant to glufosinate renewed the focus on this mode of action. Glufosinate-tolerant maize, oil seed rape, soybean and beet have all been produced under the trade name 'LibertyLink™'. They contain the enzyme phosphinothricin acetyl transferase, which detoxifies glufosinate in these crops.

EPSP synthase inhibitors

Glyphosate has been described as the most successful agrochemical of all time in terms of sales and growth of market. Its strength lies in its systemicity, allowing control of perennial weeds with troublesome rhizomes, its low non-target organism toxicity, its broad spectrum of weed control and its low soil residual activity. It is a non-selective, post-emergence herbicide that, until recently, had

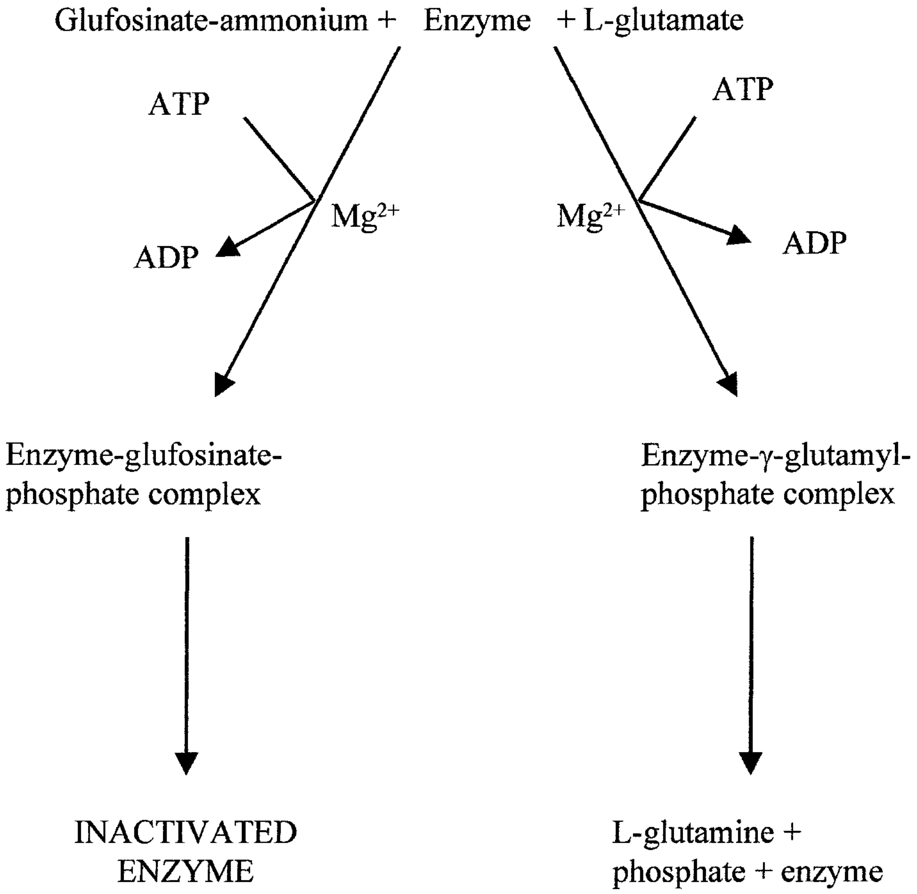
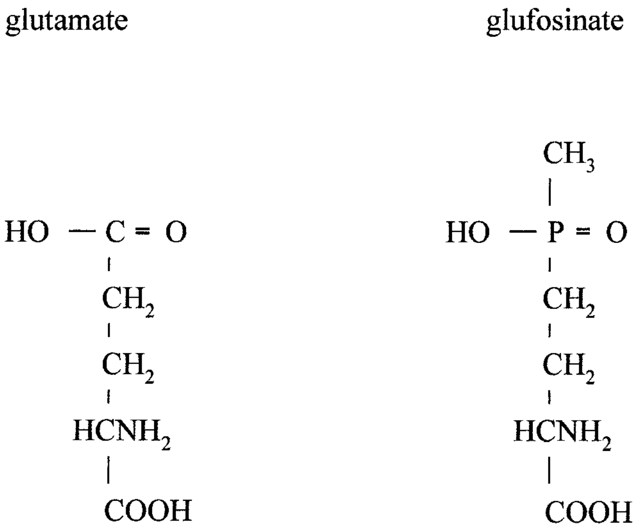


Fig. 8.7 Synthesis of glutamine from glutamate, demonstrating where the inhibition of this process by glufosinate occurs.

been used solely where total control of vegetation was required. This has changed somewhat as, similarly to glufosinate, transgenics have allowed selective control in crop situations, under the trade name ‘RoundupReady™’. The site of action of glyphosate is the enzyme 5-enoylpyruvyate shikimic acid 3-phosphate synthase (EPSP synthase; EC 2.5.1.19), which is localised mainly in the chloroplast. This enzyme is involved in the biosynthesis of the aromatic amino acids tryptophan, phenylalanine and tyrosine (and the subsequent synthesis of many secondary plant products). This biosynthesis, the shikimic acid pathway, is shown in Fig. 8.9. Its importance is demonstrated by the fact that approximately 20% of fixed carbon in green plants is passed along it. Vitamins, lignins, alkaloids and many phenolic compounds all result from products of the shikimic acid pathway.

Although once described as a competitive inhibitor with respect to phosphoenolpyruvate (PEP), it is now thought that glyphosate does not bind to the



$$\begin{array}{c}\mathrm{HO-C=O}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{HCNH_2}\\ |\\ \mathrm{COOH}\end{array}\qquad\qquad\begin{array}{c}\mathrm{CH_3}\\ |\\ \mathrm{HO-P=O}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{HCNH_2}\\ |\\ \mathrm{COOH}\end{array}$$

Fig. 8.8 Comparison of the structures of glutamate and glufosinate.

active site of EPSP synthase. It appears that it binds to a possible allosteric site, and that this causes a structural change at the active site, preventing PEP binding.

Plants treated with glyphosate can take up to three weeks to die. This ‘slow’ action probably reflects the usage of existing amino acid pools, in much the same way as is seen with ALS inhibitors. Other actions of glyphosate include a possibly enhanced auxin metabolism. Apical dominance is overcome, so lateral growth in dicotyledonous and tillering in monocotyledonous species are often noted post-treatment. This is thought to be a consequence of declining phenylalanine pools leading to less activity of phenylalanine ammonia lyase and lower concentrations of natural growth-inhibiting phenols. Observed chlorosis post-treatment may be due to inhibition of δ-ALA synthetase by glyphosate. As the shikimic acid pathway is so central to plant metabolism, it is likely that plant death results from the disruption of many vital cellular processes.

Inhibition of cellulose biosynthesis

Cellulose is a simple, unbranched, linear polymer of glucose, arranged as a β-1,4-glucan. It is an integral part of the plant cell wall and hence cellulose synthesis is imperative in order that cell wall can be synthesised. The cell wall determines to some extent both the morphology and the function of a cell, but even more importantly it controls the degree to which a cell can expand. The theory is that if cellulose biosynthesis is inhibited, then weakened cell walls will result, causing expansion of the cell and disruption of cellular processes. This in turn leads to abnormal or restricted growth and subsequent plant death. Most cellulose biosynthesis inhibitors (CBIs) are used pre-emergence, in which case seedling growth

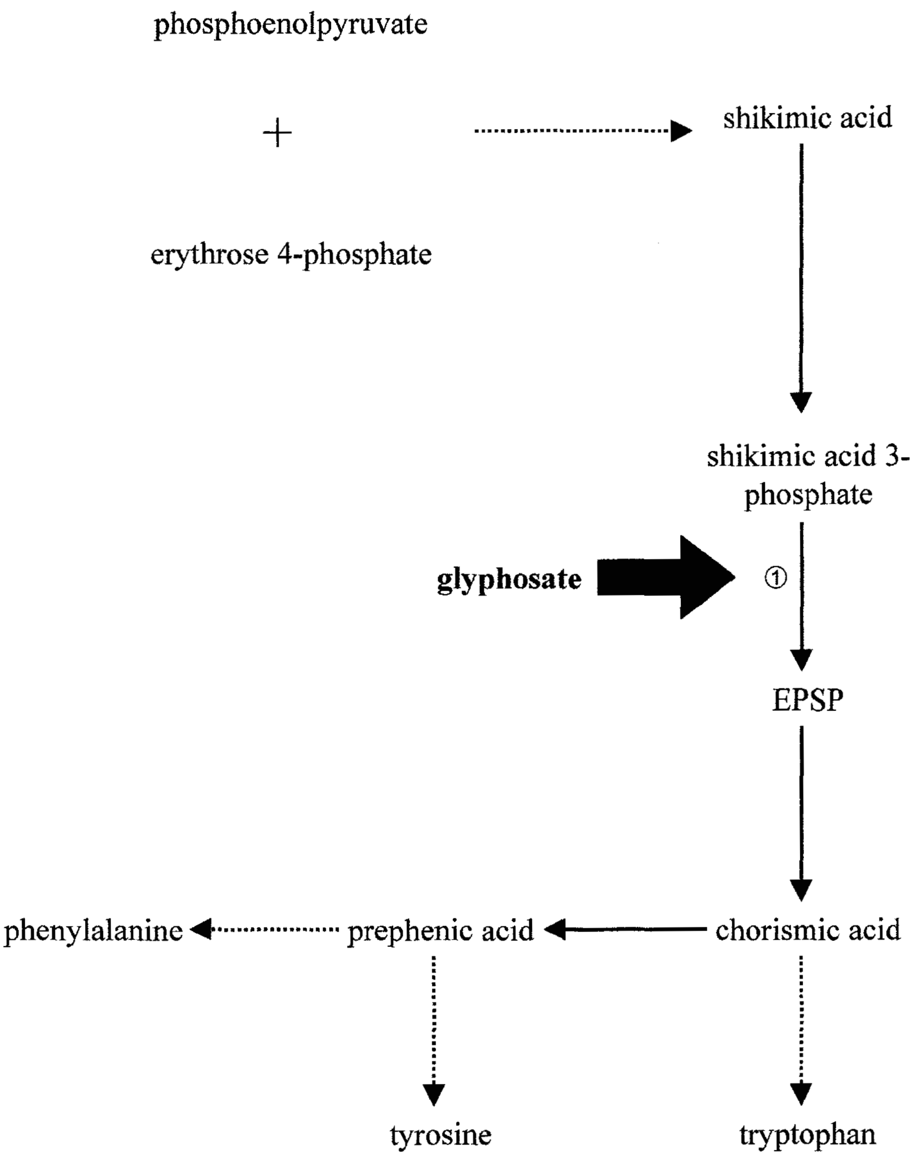


Fig. 8.9 The shikimic acid pathway, indicating the point at which herbicides act. ① = 5-enoylpyruvate shikimic acid 3-phosphate (EPSP) synthase.

is inhibited; post-emergence use of CBIs leads to stunted growth and swollen roots in treated plants. Examples of CBI herbicides are given in Table 8.8.

It appears that CBIs do not have a common site of action in the synthesis of cellulose, which is a process carried out by multienzyme complexes situated in the cell plasma membrane. Research to date has identified at least two separate

Table 8.8 Examples of herbicides that inhibit cellulose biosynthesis (CBIs)

Chemical family	Examples
Nitriles	dichlobenil, chlorthiamid
Benzamide	isoxaben

points at which CBIs inhibit. Dichlobenil (DCB) analogues have been shown to bind to an 18 kDa polypeptide associated with the multienzyme complex. It is postulated that this may be a regulator subunit associated with cellulose synthase, as it appears to be too small to be the enzyme itself. Reported effects of DCB treatment include synthesis of callose in place of cellulose. Callose is a β-1,3-glucan often formed in plants as a wounding response. It is not usually present in the cell walls of undamaged cells. It is postulated that DCB inhibits the incorporation of UDP glucose into cellulose and this is therefore shunted into callose (and xyloglucan) synthesis. Isoxaben has been demonstrated to inhibit the incorporation of [^{14}C]glucose into the cell wall. Other studies have revealed that the synthesis of both cellulose and callose is reduced by this herbicide. This suggests an inhibition of cellulose synthesis at an earlier stage than DCB, preventing incorporation of glucose into both cellulose and callose. It has been postulated that the step at which isoxaben acts may be the point where UDP glucose is formed from sucrose. Flupoxam appears to inhibit at a similar point, although less information on this herbicide's mode of action is available. A new herbicide, 5-*tert*-butylcarbamoyloxy-3-(3-trifluoromethyl)-phenyl-4-thiazolidinone, also appears to inhibit cellulose biosynthesis at the same place as isoxaben. Quinclorac, an auxinic herbicide for broad-leaf weed control, also appears to inhibit cellulose biosynthesis in some susceptible grasses although the mechanism by which it accomplishes this has yet to be deduced.

Microtubule disruptors and the inhibition of cell division

Microtubules and microfilaments are imperative for cell shape and function. They have special roles in cell division, growth and morphology. Microtubules are hollow cylindrical tubes up to 200 μm long and 25 μm in diameter. They are composed of the dimeric protein tubulin, which is made up of similar but distinct 55 kDa subunits. Microtubules are found in groups, termed arrays, in different parts of the cell at different times during the cell cycle. Four distinct functional types are described: cortical microtubules, which determine cell shape by orientating cellulose microfibrils in young, developing tissue; preprophase microtubules, which determine the plane of new cell division and hence control tissue morphogenesis; spindle microtubules, which enable movement of chromosomes during metaphase; and phragmoplast microtubules, that organize a new cell plate between daughter and parent cells after cell division, and hence also play a role in tissue morphology. Microtubules are formed from free tubulin subunits, and this is a reversible process allowing continuous construction and deconstruction to take place. The amount of tubulin that is in microtubules, as opposed to being free, can vary between 0 and 90% depending on the stage of the cell cycle. Microtubule formation is favoured by presence of microtubule-associating proteins (MAPs), magnesium ions and guanosine 5′-triphosphate (GTP). Calcium ions and GDP favour microtubule deconstruction. It is clear that microtubules are essential for both correct cellular architecture and for cell division to take place. Herbicides that affect microtubule assembly are listed in Table 8.9.

Table 8.9 Examples of herbicides that inhibit microtubule and cell division

Mode of action	Chemical family	Examples
Microtubule assembly inhibitors	Dinitroanilines	benfluralin, ethalfluralin, pendimethalin, trifluralin
	Phosphoroamidates	amiprophos-methyl, butamiphos
	Pyridazines	dithiopyr, thiazopyr
	Benzoic acids	DCPA
Inhibitors of mitosis	Carbamates	chlorpropham, propham
	Benzyl ethers	cinmethylin
Inhibitors of cell division	Chloroacetamides	alachlor, metolachlor, pretilachlor, propachlor
	Carbamates	carbetamide
	Acetamides	diphenamid, napropamide
	Benzamides	propyzamide, tebutam
	Oxyacetamides	mefenacet, fluthiamid

Dinitroanilines (e.g. trifluralin, pendimethalin) are widely used pre-emergence herbicides in dicotelydonous crops for the control of grass weeds. They also demonstrate useful selectivity in wheat. Research has demonstrated that these herbicides disrupt cell division, arresting cells in prometaphase. Nuclear membranes reform around abnormally lobed nuclei. No spindle microtubules are evident in treated cells and cortical microtubules are also affected. Root tips appear swollen after treatment, in much the same way as when plants are treated with the non-herbicidal mitotic disrupter, colchicine. The mode of action of these and of the dinitroaniline herbicides is the prevention of polymerisation of tubulin into microtubules. The precise mechanism behind this process is unclear, but it has been postulated that these herbicides accomplish it by binding to free tubulin. Although dinitroanilines inhibit both photosynthetic and respiratory electron transport at high concentrations, this inhibition is not observed with low (field rate) concentrations, further suggesting their mode of action to be linked to their inhibition of microtubule construction.

The *N*-phenylcarbamates also disrupt mitosis (as well as inhibiting phosphorylation and photosynthetic electron flow). However, although chromosomal abnormalities are noted microscopically, microtubules are found to be intact. The proposed mode of action for this herbicide class is interference with spindle microtubule organisation centres, resulting in multipolar cell division. Barban, carbetamide, propham and chlorpropham all interfere with mitosis in this manner. Chlorthal-dimethyl (DCPA) appears to block cell plate formation via disruption of organisation and production of phragmoplast microtubules. Amiprophos-methyl results in loss of microtubules and in symptoms similar to those with dinitroanilines. Propyzamide results in production of only small microtubules, and acts by binding directly to tubulin, thereby preventing it from being assembled into microtubules. Dithiopyr acts similarly to this, but binds to 65 kDa MAP rather than to tubulin. It has been suggested that MAPs may be involved in microtubule stability as well as construction and that when herbicides interfere with this, shortened microtubules result.

Auxin-type herbicides

Developed in secret during World War II as potential warfare agents, MCPA and 2,4-D were the first truly selective herbicides giving reliable broad-leaf control in cereal crops. They can be viewed as the start of a revolution in agriculture, in which chemical control largely replaced cultural methods for dealing with weeds. The success of these ‘auxin-type’ herbicides led to the development of many structural analogues. These herbicides are known as ‘synthetic auxins’ as the symptoms they produce resemble exaggerated auxin responses. Examples are given in Table 8.10.

Table 8.10 Examples of synthetic auxin-type herbicides

Chemical family	Examples
Phenoxycarboxylic acids	2,4-D, 2,4-DB, dichlorprop, MCPA
Benzoic acids	dicamba
Pyridine carboxylic acids	clopyralid, fluroxypyr, picloram, triclopyr
Quinoline carboxylic acids	quinclorac, quinmerac
Others	benazolin-ethyl

Auxins (indole-3-acetic acid, IAA, and derivatives) are endogenous plant growth regulators that play an important role in division, differentiation and elongation of plant cells. They play a role in most if not all stages of plant development and are synthesised from tryptophan in actively growing tissue. It appears that younger tissue is more sensitive to auxin effects. The action of auxins is not simply to increase plant growth. They also have the ability to inhibit plant growth, and it appears that their effect is dose-dependent. In addition, different tissues display differing sensitivities to auxins. Within plant tissues auxin concentration is tightly controlled by regulation of biosynthesis and degradation. The latter is possibly carried out by a specific IAA oxidase. In order for auxins to have an effect on plant growth there must be some form of receptor to detect auxin. A 43 kDa glycoprotein purified from maize has been identified as one such auxin-binding protein (ABP), with indirect evidence suggesting that it plays a role in auxin-dependent proton efflux from cells. It is likely that once auxin has bound to a receptor there needs to be some form of amplification of signal within the cell. It is postulated that calcium ion concentration changes and the inositol triphosphate/diacylglycerol secondary messenger system accomplish this. Auxin stimulation in cells has been demonstrated to lead to an intracellular calcium concentration up to 100 times that of an unstimulated cell.

Auxin-type herbicides are analogues of natural auxins, binding to the receptors and causing auxin-linked cellular and morphological changes. These herbicides can be described as giving the plant an auxin overdose. Plant symptoms following treatment can be separated into three distinct phases. Immediately following treatment, rapid sustained proton efflux is noted at a cellular level. Transient stimulation of photosynthesis and an increase in stomatal aperture, due to potassium ion accumulation in guard cells, are also noted. A mobilisation of carbohydrate and amino acids is also noted and an increase in mRNA leads to increased protein synthesis. All are linked to a growth response. Within one week of treatment, increased cell division and differentiation are evident in the formation of adventitious roots at stem nodes, general tissue swelling and stem, petiole and leaf epinasty. Within ten days, intracellular membranes become disrupted and organelle breakdown leads to tissue collapse and plant death.

In contrast to those herbicides mentioned above, auxin action appears to be inhibited by both the semicarbazone and phthalamate herbicides. In doing this they exhibit the opposite effect to 'auxin-type' herbicides, with symptoms of little or no growth being observed post-treatment. These substances, termed phytotrophins, severely stunt plant growth. The phthalamate naptalam is a herbicide used for pre-emergence control of broad-leaved weeds. It has been shown to act by inhibiting auxin efflux from the cytoplasm (site of synthesis) to the periplasm (export to site of action), although it is not clear whether this action is due to the naptalam binding directly to the auxin carrier or to a regulatory protein controlling auxin efflux. The semicarbazones diflufenzopyr and SCB-1 appear to inhibit auxin efflux at the same site, a plasma membrane protein. The result of this inhibition is lack of growth signals, leading to the observed stunting of growth. As the plant will neither grow nor develop, it eventually dies.

Other herbicide modes of action

In addition to the main modes of herbicide action described above, various other targets have been postulated. For example, the dinitrophenols have been demonstrated to uncouple electron transport in mitochondria, thereby separating this transport from energy-generating reactions. Increased respiration is noted after treatment, but no ATP is generated. Similar uncoupling effects in photosynthetic electron transport are also observed and it is likely that a combination of disruption of both processes leads to plant death. Release of highly reactive chlorite ions by the action of nitrate reductase appears to be the mode of action of sodium chlorate. Indeed, plants that lack nitrate reductase are resistant to the phytotoxic effects of this herbicide.

The carbamate herbicide asulam inhibits the enzyme 7,8-dihydropteroate (DHP) synthase that is involved in the synthesis of folic acid. Folic acid, as its coenzyme form tetrahydrofolic acid, is involved in many enzymic reactions, including the transfer of hydroxymethyl, formyl and methyl groups, which are especially important in the formation of amino acids, purines and pyrimidines. In inhibiting folic acid production, asulam appears to indirectly inhibit DNA synthesis, essential for cell division and plant growth and development. Metabolism of asulam to sulphanilamide has been demonstrated in *Equisetum arvense*, although this cannot be considered to be a detoxification step as sulphanilamide has the same inhibitory effect on DHP synthase. Sodium sulphanilic acid also acts at DNA synthase, and also appears to be converted to sulphanilamide in susceptible plants.

Herbicide metabolism

Plants possess a wide array of metabolic systems, both constitutive and inducible, in order to protect themselves against chemical attack (Fig. 8.10). These systems are enzymic and, to some extent, they are similar to pathways of xenobiotic metabolism found in animals. For any such system to be successful, the phytotoxic substance must be quickly metabolised to a non- (or at least less) toxic product. The rate at which this occurs can dictate whether a plant survives or succumbs to a chemical attack.

Within the plant kingdom there is a wide range of abilities to deal with different herbicides. This often provides the basis for selectivity between crop and weed, and can also explain different sensitivities displayed by different cultivars of the same crop species. It should, however, be noted that the situation is not always a clear difference between tolerant (can metabolise) and susceptible (cannot metabolise). The rate of metabolism is often important; both crop and weed may possess similar metabolic pathways, but metabolism may be at a higher rate in the crop. Differences in herbicide metabolism between crops are also observed (Fig. 8.11). Herbicide metabolism also plays a part in activating certain herbicides once they are inside the cell, and in the abilities of herbicide safeners in protecting crops from herbicide damage. An understanding of how herbicides are metabolised can increase our ability to control these processes, and ultimately to obtain better weed control agents.

Herbicide metabolism can be divided into discrete stages (as shown in Fig. 8.10). Some herbicides have been shown to undergo bioactivation within plant

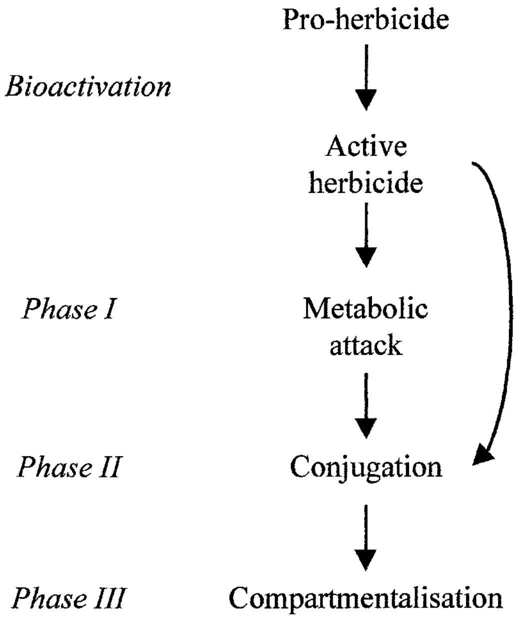
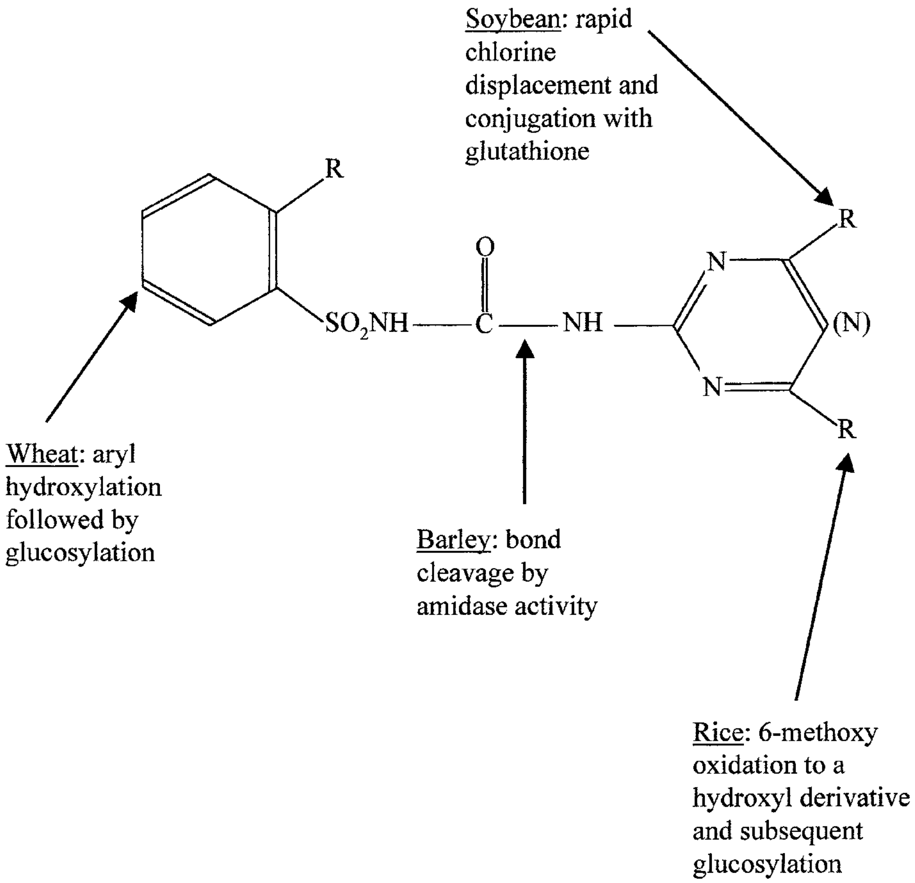


Fig. 8.10 A generalised scheme for herbicide metabolism in plants.

cells, where a pro-herbicide is converted to a phytotoxic agent by the action of plant enzymes. Before this activation they may be less or non-phytotoxic, so the plant can be instrumental in manufacturing the substance that will eventually kill it. Bioactivation can involve removal of chemical groups that have aided in herbicide uptake and this can have the added benefit of trapping the herbicide within the cell. The first step in herbicide detoxification is achieved by key enzymes that carry out two major functions. Firstly, they alter the chemical structure of the herbicide to try to render it biologically inert. Secondly, these reactions serve to increase both the reactibility and the polarity of the herbicide, so that it can be removed from the cytoplasm and either stored in the vacuole or bound to the cell wall. Metabolically, this is achieved by uncovering of polar groups (Phase I metabolism) followed by conjugation to sugars or amino acids (Phase II metabolism). In some cases polar groups may already be in place in the original herbicide structure, in which case Phase II metabolism can be carried out without the need for Phase I reactions. In other cases, conjugate formation may be a reversible process, and this is much less successful in removing phytotoxic substances.

Bioactivation

Bioactivation is the process by which pro-herbicides, which are often herbicidally inactive, are converted to phytotoxic compounds by the activity of plant enzymes



Soybean: rapid chlorine displacement and conjugation with glutathione

Wheat: aryl hydroxylation followed by glucosylation

Barley: bond cleavage by amidase activity

Rice: 6-methoxy oxidation to a hydroxyl derivative and subsequent glucosylation

Fig. 8.11 Sulfonylurea metabolism in various crops. (*Based on Beyer* et al., *1987*).

within the plant cell. This can be achieved by a wide variety of reactions, including oxidation, *N*-dealkylation, reduction, reversible conjugation, de-esterification or hydroxylation. Certain acidic herbicides are formulated as their ester forms as this facilitates uptake through the plant cuticle. Once in the cytoplasm of the cell, they are hydrolysed to the active herbicide by the action of relatively non-specific, cytoplasmic carboxyesterase enzymes. Both the aryloxyphenoxypropionate graminicides, such as fenoxaprop-ethyl, and the phenoxycarboxylic acids, such as 2,4-DB, are rapidly de-esterified in both crops and weeds. However, de-esterification may in some cases inactivate herbicides, as occurs in the metabolism of sulphonylurea esters, such as chlorimuron-ethyl, in which the de-esterified product is herbicidally inactive.

Other examples of bioactivation include hydrolysis of bromoxynil octanoate, to release the herbicidally active bromoxynil, and the conversion of EPTC to the highly reactive sulphoxide, although in the latter case both EPTC and the sulphoxide are phytotoxic. Imazamethabenz-methyl may also be regarded as a pro-herbicide. In susceptible weeds hydrolysis results in a potent inhibitor of branched-chain amino acid biosynthesis, whereas hydroxylation of the intact ester occurs in resistant maize and wheat. Bioactivation of DPX-L8747 by *N*-dealkylation in susceptible species leads to active herbicide, whereas in resistant crops hydroxylation following the formation of a glutathione conjugation of the intact pro-herbicide leads to non-toxic metabolites. These examples demonstrate how bioactivation may be a mechanism of selectivity between crop and weed. Opening of the oxadiazolidine ring of methazole, to form 1-(3,4-dichlorophenyl)urea, and *N*-demethylation of pyridazinone to form a potent phytoene desaturase inhibitor, further demonstrate the wide range of chemical reactions that can lead to bioactivation. In the case of the bioherbicide bialaphos, a tripeptide obtained from *Streptomyces*, cleavage results in the release of glufosinate, which is also used as a herbicide in its own right. Interestingly, resistance to the herbicide triallate in a biotype of *Avena fatua* has been demonstrated to be due to a reduced ability to convert triallate to the phytotoxic product triallate sulphoxide. This is the only reported instance of resistance being due to the inability of a weed to bioactivate a herbicide.

Metabolic attack (Phase I metabolism)

Although not the only means by which it is achieved, the ability of a plant to rapidly detoxify a herbicide is the single most important factor relating to herbicide selectivity, as shown for chlorotoluron in Fig. 8.12.

The most important group of enzymes carrying out this role during Phase I metabolism are the cytochrome P450 mono-oxygenases (P450s). Part of a large family of haem proteins, these enzymes are found in all parts of the plant. They are membrane-bound and are present at very low concentrations. The reaction they carry out is summarised in Fig. 8.13. One atom from molecular oxygen is incorporated into the substrate (R), and the other atom is reduced to form water. The electrons required for the activation of oxygen are donated from NADPH via NADPH–P450 reductases, which are membrane-bound enzymes. All P450s have a highly conserved region of ten amino acids surrounding the haem group, and it is this region that is responsible for the binding of O_2, its activation and the transfer of protons to form water. The rest of the P450 amino acid sequences are highly variable, which probably explains the wide variety of reactions and substrate specificity shown by this enzyme superfamily.

The main reactions catalysed by P450s are shown in Fig. 8.14. P450s in plants have roles in the biosynthesis and metabolism of a wide variety of compounds, including terpenes, flavonoids, sterols, hormones, suberin and phytoalexins. They are also induced by pathogen attack, xenobiotics and by stress induced by light, unfavourable osmotic conditions and wounding, and following infection.

Genetic analysis has revealed that *Arabidopsis* contains approximately 300 P450s and there are predicted to be considerably more than this in most plants.

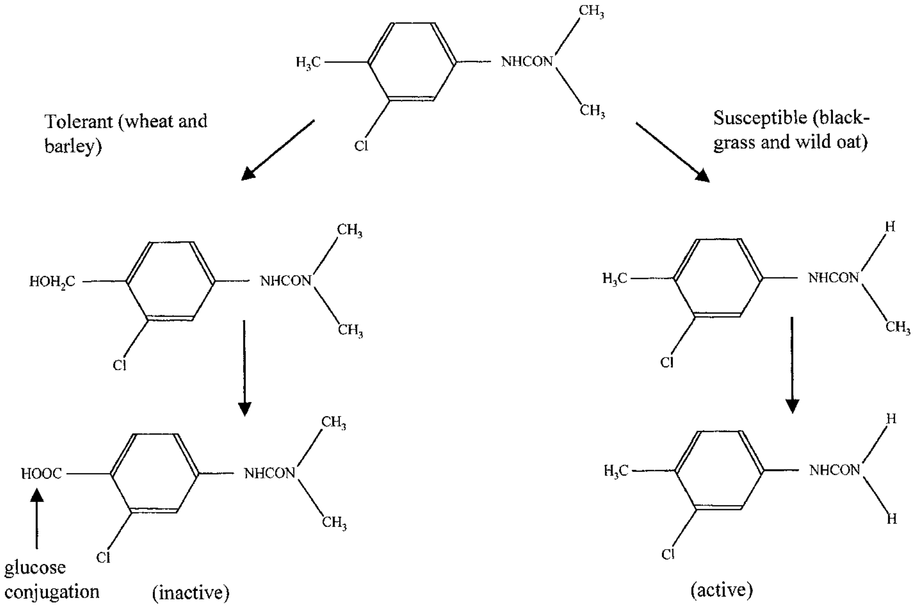


Fig. 8.12 Metabolism of chlorotoluron in tolerant and susceptible species.

The sheer number of P450s present further implies their multiple substrates and roles. In herbicide metabolism the main reactions carried out by P450s are hydroxylation and dealkylation, which progresses via a hydroxylation step.

Examples of herbicides metabolised by P450s in plant systems include sulfonylureas (including primisulfuron, nicosulfuron, prosulfuron, triasulfuron and chlorimuron), substituted ureas (CTU, linuron), chloroacetanilides (metolachlor, acetochlor), triazolopyrimidines (flumetsulam), aryloxyphenoxypropionates (diclofop), benzothiadiazoles (bentazon) and imidazolinones (imazethapyr). Selectivity to herbicides can be due to ability of the crop to metabolise herbicides via P450s, an ability that may not be possessed by associated, susceptible weeds. However, in some cases this metabolism is not enough to prevent crop damage, because of either low P450 metabolism or phytotoxicity of products produced by these reactions. In these cases crop

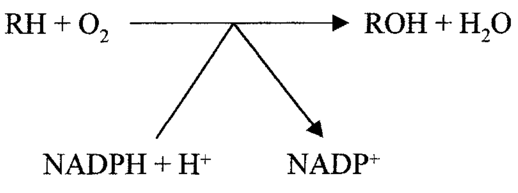


Fig. 8.13 The central reaction of cytochrome P450 mono-oxygenases. R represents a wide variety of molecules upon which P450s act.

damage will only be prevented if reactions from Phase II (conjugation) are successful in carrying out the detoxification.

Conjugation reactions (Phase II metabolism)

Conjugation reactions involve the attachment of the herbicide, or one of its metabolites, to another molecule, usually either a sugar or an amino acid derivative. These reactions appear to have a variety of roles in plant metabolism, including conjugation of endogenous phenolic metabolites. Conjugation reactions usually follow Phase I reactions that have successfully revealed appropriate chemical groups that will allow conjugation to take place. However, it also seems that conjugation reactions can be the first stage in herbicide metabolism if the necessary groups are present in the parent herbicide.

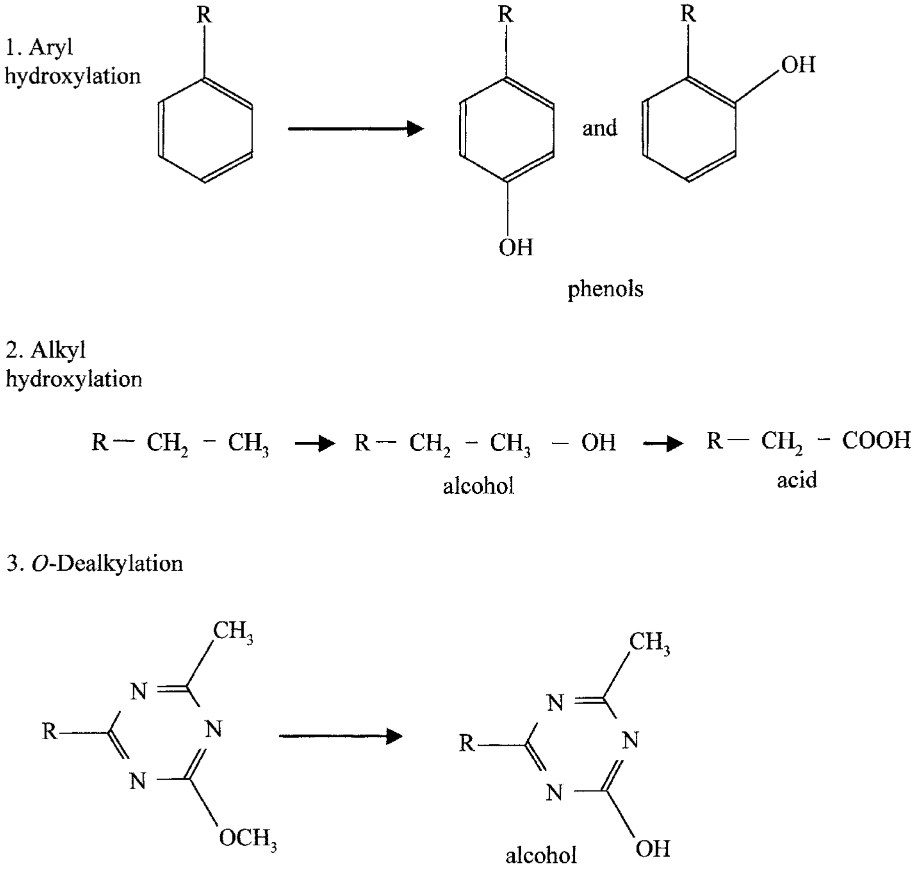


Fig. 8.14 The main reactions carried out by cytochrome P450 mono oxygenases (P450s).

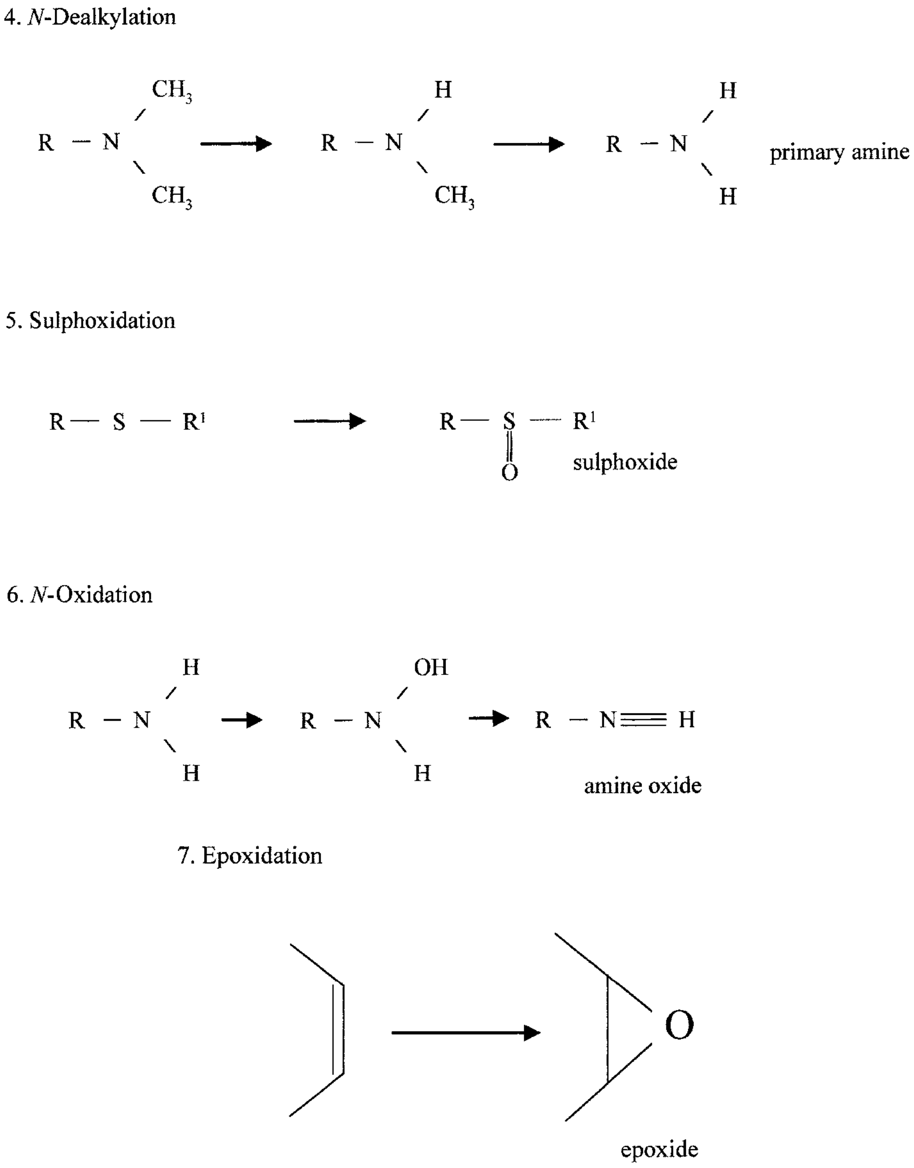


Fig. 8.14 The main reactions carried out by P450s (*continued*).

Conjugation can take place with glutathione, sugars or amino acids and results in increased solubility, and often reduced toxicity, of the product. In addition, conjugation may play an important role in aiding transportation of metabolites to the cell vacuole. Conjugation to sugars can be as *O*-glucosides, *N*-glucosides or glucose esters. This mode of conjugation has been demonstrated in soybean against chloramben and a metabolite of propanil (3,4-dichloroaniline), where UDP–*N*-glucosyl transferases carry out the reaction. 3,4-Dichloroaniline is further conjugated by addition of a malonyl moiety, via malonyl transferases. Conjugation of phenoxycarboxylic acids to amino acids in some plant species does not detoxify the herbicide, and is readily reversible. Similar reactions are reported for triclopyr in cereals and chickweed. *S*-conjugation of 4-hydroxy-chlorpropham, a metabolite of chlorpropham, with cysteine is reported in oats (via the aryl ring). In wheat, chlorfenprop is cysteine-conjugated following hydrolysis of the parent ester. In maize, primisulfuron is mainly metabolized by hydroxylation at the phenyl or pyrimidine ring (by P450s) followed by glucosylation (Fig. 8.15). This conjugate is then transported to the vacuole, as has been demonstrated *in vitro*, by active transport. It appears that conjugate formation in this case is absolutely necessary for transportation to take place.

The most widely studied conjugation reaction in relation to herbicide detoxification is that of glutathione, carried out by the enzyme family glutathione *S*-transferase (GST). In most cases the resultant conjugates are more soluble and less toxic. As GSTs are a large group of similar enzymes, differences in the spectrum of GSTs present play an important role in selectivity of herbicides. Glutathione (GSH) is a tripeptide (ξ-glutamylcysteinylglycine) that is found in most organisms. It has a range of endogenous functions involving its abilities to detoxify and act as a redox buffer. GST activity against herbicides was first demonstrated in plant tissue in maize extracts against atrazine. Since this observation, GST activity against a wide variety of herbicides has been reported (Table 8.11). As with other conjugate types, GSH conjugation can be carried out against the parent herbicide if an appropriate conjugating group is present, or can follow Phase I metabolism. An example of the latter is the conjugation of glutathione with thiocarbamates only after they have undergone conversion to their corresponding sulphoxides.

Crops are often reported to possess higher GST activities against herbicides than susceptible weeds, and this might offer some degree of selectivity between crop and weed. Activity against chloroacetamides (maize, wheat, sorghum, rice), oxyacetamides (maize), atrazine (maize, sorghum), fenoxaprop, fluorodifen, flupyrsulfuron-methyl, dimethenamid (all wheat) and the sulphoxide metabolite of EPTC (sorghum) have all been reported. In soybean, homoglutathione is found in place of glutathione. Conjugations utilising this compound against several chloroacetanilides, the diphenyl ethers acifluorfen and fomesafen, and the sulphonylurea chlorimuron-ethyl are all reported in this crop. In addition to selectivity, GSTs have also been implicated in playing a role in herbicide resistance in a variety of weeds. In blackgrass, a biotype resistant to CTU and fenoxaprop-ethyl demonstrated approximately double the GST activity of susceptible biotypes. This suggests that GSTs, as well as P450s, may play a role in enhanced metabolism resistance in this species. In velvetleaf, resistance to atrazine has also been demonstrated to be due to higher conjugation of this herbicide to glutathione.

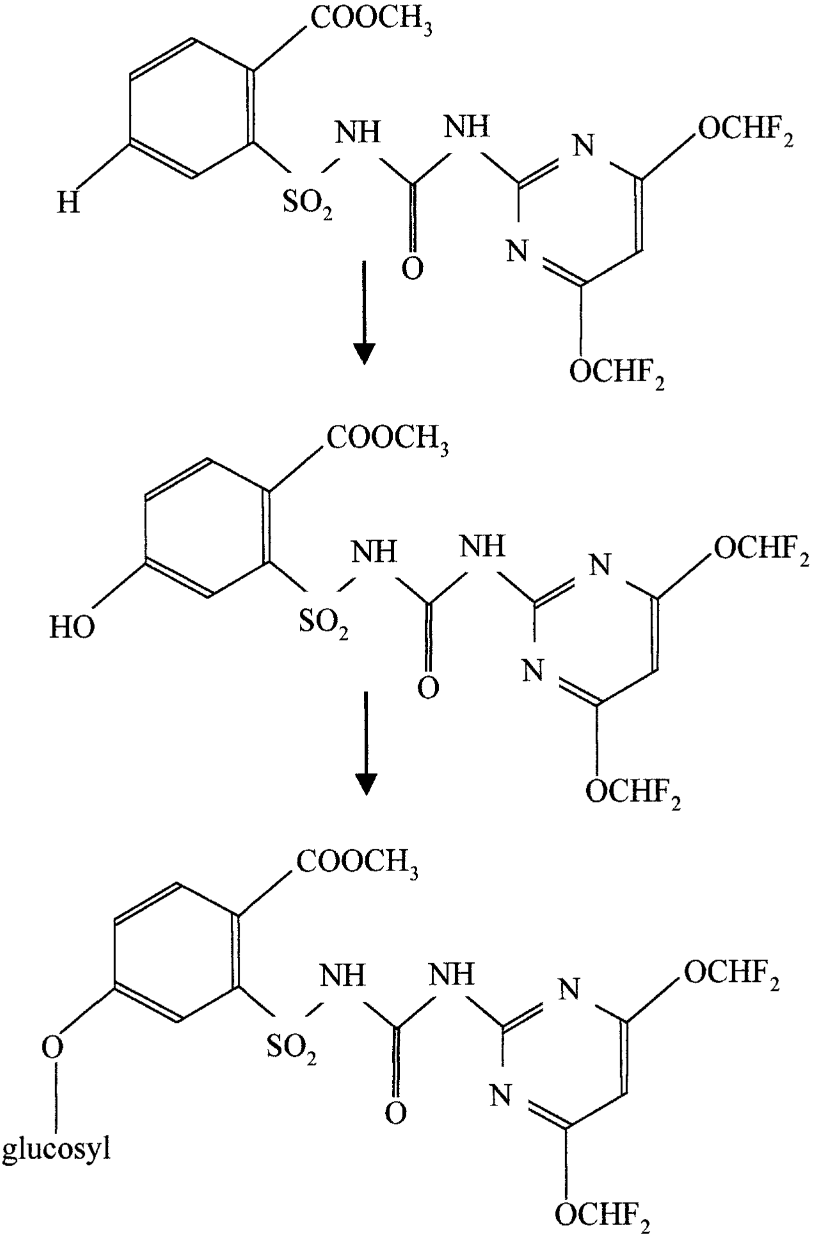


Fig. 8.15 Metabolism of primisulfuron by *O*-glucosyl conjugation.

Table 8.11 Examples of some herbicides metabolised by GSTs in various plant systems

Chemical family	Examples
Chloroacetamides	alachlor, acetochlor, metolachlor, pretilachlor,
Triazines	atrazine
Aryloxyphenoxypropionates	fenoxaprop
Thiocarbamate	EPTC
Diphenyl ethers	acifluorfen, fomesafen
Sulfonylureas	chlorimuron-ethyl, triflusulfuron-methyl

Compartmentalisation (Phase III metabolism)

Once metabolised to a less or non-phytotoxic product, a metabolite may be compartmentalised in much the same way as plant secondary metabolism products are moved for storage. The place of storage is either the vacuole or in association with the cell wall. Recent identification of a membrane-bound glutathione-dependent ABC pump in the vacuolar membrane suggests that Phase II conjugation to glutathione might serve to facilitate in the movement of metabolites and could be considered as a way of 'tagging' molecules for movement into the vacuole. Once conjugates are situated in the vacuole, sequential removal of peptides from glutathione is carried out by peptidases. This results in the metabolite being conjugated to glutamylcysteine and possibly just cysteine. It is postulated that this allows for recycling of amino acids back to the cytoplasm and in addition may prevent the conjugated metabolite from being exported back there, as it no longer is a full glutathione conjugate. This pumping mechanism may have the additional benefit of stopping the build-up of GSH conjugates from inhibiting cytoplasmic GST activity, as some conjugates have been demonstrated to be powerful competitive inhibitors of GSTs. Once the metabolite conjugate has entered the vacuole it may be further metabolised, stored there or excreted across the plasma membrane to the extracellular matrix. Transport of glucosylated herbicides into the vacuole is also reported. This requires ATP, so is also active transport. However, it appears that the membrane pump carrying this out is distinct from the GSH pump system.

Herbicide safeners

Selectivity of herbicides through differences in target site or herbicide metabolism between crop and target plant has already been mentioned. In addition, incorporation of a herbicide safener with the herbicide can be used in some cases to protect the crop from herbicide damage whilst still allowing satisfactory weed control.

Dichlormid, a safener used with EPTC, prevents inhibition of fatty acid, gibberellins, acetyl-CoA, carotenoid and epicuticular wax biosynthesis in crops.

The mode of action of this safener has yet to be established, but it has been postulated that it may compete with herbicide binding, enhance synthesis of the target enzyme, in this case a desaturase, or stimulate synthesis of a less sensitive isozyme of the target site.

In order to establish whether a safener has a direct effect on herbicide binding it is necessary to carry out a study *in vitro*. This has been done for both chlorsulfuron and fenoxaprop-ethyl/sethoxydim in maize. Neither 1,8-naphthalic anhydride (NA), a safener for chlorsulfuron, nor fenchlorazole-ethyl, a safener for the 'fops' and 'dims', displayed any protection *in vitro*. This suggests that, with these safeners, direct interaction with either the herbicide or the target site is not the mechanism that protects the crop. Although dichlormid, NA and oxabetranil have been demonstrated to raise the activity of ALS in maize in some studies, it is felt that this is not the primary mode by which crop protection from herbicides is achieved. Other studies suggest that this protection is not conferred by differences in herbicide uptake by crops.

It is generally felt that safeners act by increasing metabolism of herbicides in crops, thereby reducing their phytotoxic effects. They may have effects on either Phase I or Phase II metabolism. NA and dichlormid have been demonstrated to accelerate oxidative metabolism, by P450s, of chlorsulfuron, metsulfuron-methyl and sulfometuron-methyl in maize. It appears that many safeners induce cytochrome P450 mono-oxygenases, so preparing the crop plant for metabolising herbicides. In addition, *in vitro* study has demonstrated that NADPH-dependent microsomal herbicide metabolism is increased by safener treatment, further implicating P450s. One non-P450 effect of safeners is the inhibition of EPTC sulphoxidation in maize by dichlormid. As EPTC sulphoxide is more toxic than the parent herbicide, prevention of this sulfoxidation would protect the crop to some degree. Protection from chloroacetanilides and thiocarbamates by various safeners has been demonstrated to be due to enhanced GSH conjugation. Both increased GSH concentration and enhanced GST activity are observed in safener-treated crops. Further examples of this are reported for fenchlorazole-ethyl-protected wheat and benoxacar-protected maize, offering safener protection against fenoxaprop-ethyl and metolachlor respectively.

A further example of a safener affecting Phase II metabolism is increased glucose conjugation of clodinafop-propargyl in wheat when it is protected with the safener cloquintocet-mexyl. In this case it is unclear whether this is due to an increase in UDP-glucosyl transferase activity or an increase in available glucose. Studies to date therefore firmly suggest that the main mode of action of herbicide safeners is to increase the ability of crops to metabolise herbicide. It may be that the safeners elicit a similar response to that caused by phytotoxic chemicals, but as they are relatively non-phytotoxic this primes the metabolism of the crop plant to deal with the accompanying herbicide.

Concluding remarks

An understanding of the modes of action and metabolism of herbicides not only provides knowledge of crop protection and how it might move forward, but has also aided in the further understanding of many biochemical processes in plants. As modes of action are researched further it is likely that this understanding will continue to grow. This deeper knowledge of plant biochemistry and physiology will then aid in the discovery and development of safer, more accurate and more effective herbicides.

The main herbicide modes of action include:

- Disruption of photosynthesis
- Inhibition of pigment biosynthesis
- Inhibition of lipid biosynthesis
- Inhibition of amino acid biosynthesis
- Disruption and inhibition of cell division
- Auxin 'overdose'

Herbicide metabolism can be divided into four distinct phases:

- Bioactivation
- Phase I – chemical
- Phase II – conjugation
- Phase III – compartmentalisation

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Chapter 9
Herbicide Formulation and Delivery

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Introduction

> 'The main objectives of formulation can be summarized as follows: to provide the user with a convenient, safe product which will not deteriorate over a period of time, and to obtain the maximum activity inherent in the active ingredient.' (Knowles, 1998.)

Weed control with herbicides involves delivering the active ingredient (hereafter a.i.) from the manufacturer to the user, and then from the user to the final site of biological activity. The formulation chosen for the herbicide provides the vehicle for this delivery system, and must encompass many, often conflicting, requirements. There is a continuing challenge to use herbicides with minimal harm to the environment, groundwater and human health. In particular, during the 1990s there was a considerable increase in the legal controls on pesticide use. Developing safer formulations forms an important response to these pressures, especially when combined with improvements in application technology. As a result, there have been clear trends in formulation and packaging, aimed at increasing operator safety, reducing environmental contamination and reducing residues. Such changes have only been possible because of the developments in colloid and surface chemistry and process technology which have been applied to pesticides.

This chapter describes the principles of herbicide formulation, including the packaging of products, the effect of formulation on a.i. efficacy, and the additives and adjuvants that are intended to enhance herbicide performance. The dominant method for applying herbicides in the UK and northern Europe is by spraying formulations that have been heavily diluted in water. Before the different formulation types are reviewed in detail, it is useful to describe the general characteristics of surfactants, which are found in almost all formulations. Surfactants have physical properties which make them suitable for a number of roles in formulation.

Surfactants, surface tension and emulsions

Surfactant molecules are amphipathic, i.e. they consist of two parts which are compatible with different phases. Most commonly, the molecules have a hydrophilic head and a hydrophobic (or lipophilic) tail. At an interface the surfactant molecules become orientated across the interace, so as to keep their heads and tails in the appropriate phases. This molecular orientation results in a reduction of the interfacial tension. The interface may be oil–water, oil–solid, oil–air, water–solid or water–air. For example, at an oil–water interface the surfactant molecule heads are in the water and tails in the oil, whilst at an air–water interface the heads are in the water and the tails in the air.

When surfactant is added to an aqueous solution, as the surfactant concentration is increased more surfactant molecules populate the air–water interface, and the surface tension is reduced. This reduction in surface tension with increasing surfactant concentration continues until the interface is saturated with surfactant molecules. At this point, called the critical micelle concentration (CMC), increasing the surfactant concentration does not reduce the surface tension further since no more surfactant molecules can reside at the interface. Instead, above the CMC the 'excess' surfactant molecules form aggregates, or micelles, within the liquid. In micelles the surfactant molecule heads are in the water with the tails packed inside the micelle.

The surface tension of a surfactant solution can be characterised by two measurements. The equilibrium surface tension (EST) is, unsurprisingly, the surface tension measured when the surface is in equilibrium. With a surfactant present, the population of surfactant molecules at the surface is constant at equilibrium. Above the CMC, this population represents the maximum number of surfactant molecules per unit surface area. However, if the surface is stretched its area increases, and more surfactant molecules can be accommodated on it. Since it takes time for surfactant molecules to move from the bulk liquid to the surface, the number of molecules per unit area varies with time, causing the surface tension to vary. The instantaneous value of the surface tension at a given surface age (the time after the surface was last at equilibrium) is the dynamic surface tension (DST). The only time when dynamic surface tension operates is when the surface tension is changed by the presence of a particular molecule – a pure solvent such as water has a constant surface tension. So, when the concentration of surfactant in an aqueous solution is increased, the EST and DST both decrease until the CMC is reached. Increasing the surfactant concentration above the CMC continues to reduce the DST, but does not change the EST. Most surfactants in formulations and adjuvants are present at concentrations above their CMC. Figure 9.1 illustrates different dynamic surface tension data for two model surfactants.

One of the major uses of surfactants in formulations is to create emulsions. An emulsion is a stable mixture of two immiscible liquids (e.g. oil and water), with one liquid forming droplets in the other one. Without the emulsifier to stabilise these droplets the two liquids would separate; for example, at oil–water droplet interfaces the surfactant molecule heads are in the water with the tails in the oil. The emulsifier is often a blend of two or more surfactants, chosen to stabilise a particular liquid mixture and hold the emulsion droplets within a desired size range. Emulsions may also be more complex than just two liquids and can include solid particles. A special type of emulsion is formed by solubi-

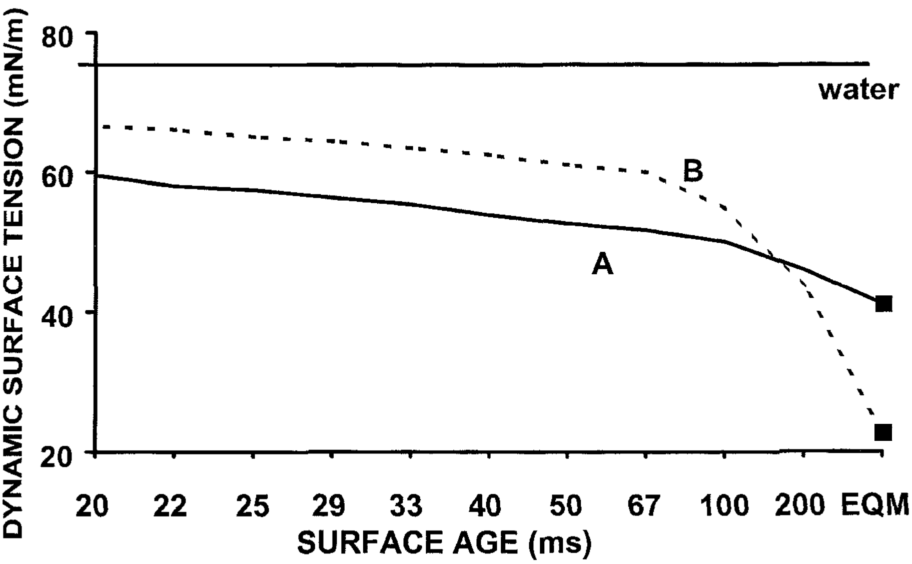


Fig. 9.1 Dynamic surface tension profiles of two model surfactants, A and B. EQM is equilibrium surface.

lisation, where water insoluble chemicals (e.g. a.i.s) are contained inside surfactant micelles.

Surfactants are also used in formulations as wetting and dispersing agents for particles in water. Where particles are suspended in water, surfactant adsorption onto the particles' surfaces reduces aggregation, so maintaining a more uniform particle size and distribution. The presence of the surfactant on the particle surface also improves wetting of the particle. In turn, this improves the mixing and dispersion of particles both during manufacture and when mixed with water in the spray tank. Similarly, surfactants are added to solid granule formulations. During mixing in the spray tank these surfactants enhance the penetration of water into the granules, and then act as wetters and dispersants to the granule fragments.

Whilst there are additional minor functions for surfactants in formulations, their other major use is to enhance the biological performance of the a.i. This is discussed later in this chapter, in terms of the effect of liquid properties on herbicide performance.

Herbicide formulations

The need for a range of formulations arises from the widely varying physical and chemical properties of a.i.s. Some a.i.s are liquid and some are solid; they may be largely insoluble, soluble in water or soluble in hydrocarbons. Choice of formulation type may also take into account the particular mode of action of the a.i. or a particular application method.

The prime aim of formulation is to produce a herbicide which (1) is profitable to the manufacturer, (2) remains stable and safe during transit and storage, (3) optimises the biological activity of the a.i. for the intended application method and (4) minimises the risk to operator, environment and consumer.

The physicochemical properties of the a.i. must be the first consideration in deciding which type of formulation to use. Other factors that must be considered are:

- Mode of action and activity
- Safety in use and as a residue
- Ease of use with chosen application method
- Cost and ease of manufacture
- Packaging options
- Market preferences
- Legal restrictions

Some a.i.s are suitable for a number of different formulation types, while others offer more limited formulation options. Formulations can be classified solid or liquid. In addition, there are often clear distinctions between formulations for use with spraying and non-spraying application methods, and between those for agricultural and amenity (non-agricultural) markets. Formulation types are named according to the Global Crop Protection Federation (GCPF, formerly GIFAP) catalogue. Table 9.1 summarises the main advantages and disadvantages for each formulation type.

Solid formulations

Granules (GR)

Granules are the major non-spray application formulation. Designed to be spread on the field, they are usually used for pre-emergence herbicides. Granules are also used extensively for rice herbicides. Manufacture involves either dissolving the a.i. into a carrier with a solvent, or coating a carrier with the a.i. The granules are uniform in size (generally less than 1 mm) and neither aggregate nor form dust during transport, storage and application. They also flow freely, and are designed to disintegrate in the soil. Surfactants or other co-formulants may be present to aid disintegration and increase a.i. activity. The a.i. concentration is, typically, 1–40%.

Wettable powders (WP)

Wettable powders are an old formulation type, designed for application after mixing with water. They are manufactured by grinding or milling the a.i. and an inert filler. This filler inhibits aggregation during storage as well as making

Table 9.1 Main advantages and disadvantages of the different formulation types

Formulation type	Main advantages	Main disadvantages
Granules	Easy soil application Long residual activity	Bulky Lower active ingredient concentration
Wettable powder	Cheap and easy to manufacture Higher active ingredient concentration	Safety hazard from dust Difficult to handle
Water-dispersible granules	Safer and easier to handle than WP Higher active ingredient concentration	Bulky Expensive to manufacture
Tablet	Very safe and easy to handle	Suitable for highly active active ingredients only
Soluble liquid	Cheap and easy to manufacture Can 'build in' adjuvants	Few suitable active ingredients Lower active ingredient concentration
Suspension concentrate	Higher active ingredient concentration Can 'build-in' adjuvants	Difficult to manufacture Difficult to empty and clean containers
Emulsifiable concentrate	Easy to manufacture, stable emulsion Surfactants act as 'built-in' adjuvants	Flammability and safety risks High skin penetration
Concentrated emulsion	Safer, lower skin penetration, less flammable than EC Surfactants act as 'built-in' adjuvants	Expensive and difficult to manufacture Difficult to empty and clean containers
Suspoemulsion	More than one active ingredient can be included Surfactants act as 'built-in' adjuvants	Expensive and difficult to manufacture
Microemulsion	Stable emulsion Surfactants act as 'built-in' adjuvants	Expensive to manufacture Lower active ingredient concentration
Multiple emulsion	More than one active ingredient can be included Surfactants act as 'built-in' adjuvants	Expensive and difficult to manufacture
Microcapsules	Safer to handle and less environmental contamination Longer duration for active ingredient activity	Expensive and difficult to manufacture Lower active ingredient concentration
Gel	Highly stable, easier to handle	Expensive and difficult to manufacture Lower active ingredient concentration

processing easier. Surfactants are included to improve wetting and dispersion during mixing with water. The powder should not aggregate during transport and storage, and should flow freely. It is designed to give a uniform particle size and dispersion of the a.i. in the spray tank. The a.i. concentration is, typically, 25–80%.

The significant disadvantage with wettable powders is that a toxic dust is formed, presenting a safety hazard when they are handled. This has led to the replacement of wettable powders with water-dispersible granules.

Water-dispersible granules (WG)

Water-dispersible granules are also designed for application after mixing with water. They can be manufactured using a number of different methods, which adds to the range of a.i.s that can be used. Manufacturing costs are higher than for wettable powders. The a.i. is combined with an inert carrier (and, sometimes, also water-soluble salts) and surfactants which are added to improve wetting, disintegration and dispersion. Dry granules are smaller than 2 mm and are designed to disperse fully in less than 2 min. They neither aggregate nor form dust during transport and storage, and also flow freely. The a.i. concentration is, typically, 20–90%.

Tablets (TB)

Tablets are a special form of water-dispersible granule, being larger and requiring a more powerful disintegrating agent; they are often effervescent. They offer easier dose measurement and safer handling than other solid formulations. The a.i.s that are most suitable for tablet formulations are highly active, so that high a.i. concentrations are not necessary. Tablets have been used in Japan for controlled release of rice herbicides. The tablet sinks to the bottom of the water in the field, and then releases the a.i. slowly as it dissolves.

Liquid formulations

Soluble liquids (SL)

Also known as a solution concentrate, the soluble liquid is an older formulation, simply being a water-soluble a.i. added to water. Although this is a very stable and easy-to-pour formulation, antifreeze is often added. Preservatives may be added to inhibit mould and bacteria. If surfactants are added, their purpose is to enhance the biological activity of the a.i. The a.i. concentration is, typically, 20–50%.

Suspension concentrates (SC)

Formulated since the 1970s, suspension concentrates are a.i. particles suspended in water, or sometimes oil. They are manufactured by wet-milling the a.i. with surfactants and water. The resulting particles are smaller than 10 µm. A stable, easily poured formulation is achieved by adding, in addition to the surfactants for wetting and dispersion, an anti-settling agent or thickener. Solvents may also be added to improve stability and dispersion. Again, antifreeze and preservatives are often added. Extra surfactants may be added to enhance a.i. biological activity. The a.i. concentration is, typically, 20–50%.

Emulsifiable concentrates (EC)

Emulsifiable concentrates are another older formulation used for a.i.s that are oily liquids or low-melting-point waxy solids. A stable, easily poured formulation is manufactured by dissolving the a.i. in a hydrocarbon solvent or blend of solvents and adding surfactants. The function of the surfactants is to induce spontaneous emulsification and create a stable and uniformly dispersed emulsion when the formulation is mixed with water. Emulsion droplets in the spray tank are smaller than 5 µm. Again, extra surfactants may be added to enhance a.i. biological activity. The a.i. concentration is, typically, 10–70%.

In recent years hydrocarbons have become less acceptable due to their flammability, environmental and health risks. Alternative, more acceptable solvents (such as alkylated vegetable oils) have been used. Unfortunately, these are more expensive and often do not perform as well as hydrocarbons. As a result, emulsifiable concentrates have been steadily replaced by a range of oil-in-water emulsions.

Oil-in-water emulsions (EW)

Oil-in-water emulsions can be thought of as emulsifiable concentrates added to water. However, their emulsions are inherently unstable, and require a careful choice of surfactants plus a thickening agent to give an acceptable shelf-life before the emulsion degrades. In addition, preservatives are needed with some thickeners. Oil droplets in the formulation are smaller than 2 µm. Oil-in-water emulsions are easily poured, and form a stable and uniformly dispersed emulsion when mixed with water. The a.i. concentration is, typically, 20–50%.

Water-in-oil emulsions (WO)

Water-in-oil emulsions can be thought of as reverse oil-in-water emulsions, i.e. the a.i. is dissolved in water droplets forming an emulsion in an oil carrier. Similar stability problems exist, and surfactants are needed for spontaneous emulsification if the formulation is to be mixed with water. Water-in-oil emulsions are suitable for ultra-low-volume applications where the formulation is used undiluted, e.g. with spinning disk applicators. They are easily poured, and form a stable and uniformly dispersed emulsion when mixed with water. The a.i. concentration is, typically, 20–50%.

The term 'concentrated emulsion' (CE) can be used to describe both oil-in-water and water-in-oil emulsions.

Suspoemulsions (SE)

Suspoemulsions are mixed formulations containing both solid and liquid a.i.s, which can be either the same a.i. or two different ones. They are like a mixture of an oil-in-water emulsion and a suspension concentrate. The liquid component is an a.i. dissolved in oil droplets which form an emulsion in water, whilst the solid a.i. is suspended in the water. The stability problems are similar to those for oil-in-water emulsions, but more complex. Different surfactants are included in the formulation to disperse the solid particles and emulsify the oil droplets. A thickener is essential, and there may be a preservative. The oil droplets are generally smaller than 2 μm. Again, the formulation is easily poured and forms a stable and uniform dispersion of particles and emulsion droplets when mixed with water. The a.i. concentration is, typically, 20–70%.

Microemulsions (ME)

Microemulsions are a special case of the oil-in-water emulsion. An a.i. is dissolved in oil or solvent, and this mixture is solubilized inside swollen micelles in an aqueous solution. (A microemulsion can also be based on a water-in-oil emulsion, i.e. with a.i. plus water inside micelles which are in oil. However, these are rare for pesticides.) Surfactants are paired: one is water-soluble and the other oil-soluble. The emulsion droplets are smaller than 0.1 μm. Microemulsions are stable and easily poured, and form a stable and uniformly dispersed emulsion when mixed with water. The a.i. concentration is, typically, 10–40%.

Multiple emulsions

Multiple emulsions are an emulsion in an emulsion, and can be water-in-oil-in-water or oil-in-water-in-oil. Pesticides are usually water-in-oil-in-water emulsions, i.e. water droplets emulsified inside oil droplets which are emulsified in a water carrier. Again, different surfactants are needed in the formulation to emulsify the oil and water droplets. A thickener and a preservative may also be needed. The presence of multiple emulsions allows the inclusion of more than one a.i. While complex and costly, multiple emulsions can reduce the toxicity of a formulation when compared with a single emulsion, and may also offer a crude form of controlled release. They are easily poured, and form a stable and uniformly dispersed emulsion when mixed with water. The a.i. concentration is, typically, 20–60%.

Controlled-release formulations

Controlled-release, or delayed-release, formulations aim to bind the a.i. so that it is released by an external trigger. Their main aim is either to increase the amount of a.i. reaching the biological target or to extend the duration of a.i. activity by not releasing all the a.i. at once. In addition, the formulation should be less toxic and safer to handle, and it should reduce environmental contamination. There are various options for controlled release, including the multiple emulsions described previously. Polymer-coated granules are another option; the polymer degrades either at a constant rate or under certain triggering conditions such as exposure to ultraviolet light or contact with a given chemical secreted by a plant.

Microcapsules (CS)

Microcapsules are a liquid controlled-release formulation. They are manufactured by polymerising a fine oil-in-water emulsion (with the a.i. in the oil) to give a thin polymer shell around each oil droplet. This polymer shell will degrade once it is no longer stabilised by the liquid carrier (i.e. once it is a dry deposit on the plant). Degradation may be either at a constant rate or under certain triggering conditions. The microcapsules form a suspension so, as for a suspension concentrate, surfactants are added for wetting and dispersion of the microcapsules in the spray tank. An anti-settling agent or thickener is also needed. Microcapsule formulations are stable and easily poured, and form a uniform dispersion when mixed with water. The a.i. concentration is, typically, 10–30%.

Gels (GL or GW)

Gels, or gelatinised fluids, can be thought of as thickened emulsifiable concentrates (GL) or thickened oil-in-water emulsions (GW). They are very viscous, so do not pour easily. Instead of being supplied as a liquid, they are often packaged as premeasured doses in water-soluble bags which make handling safer and reduce environmental contamination. Gels are formulated to disperse and mix thoroughly in water, giving a stable and uniform emulsion in the spray tank. The a.i. concentration is, typically, 20–50%.

Other pesticide formulations not used for herbicides

Seed treatments (DS, WS, LS, FS), dustable powders (DP), smokes, fogs and fumigants are not used for herbicides, so are not considered here.

Formulations for low-volume (LV) and ultra-low-volume (ULV) use

Many hand-held herbicide application systems, particularly in the amenity sector, use low-volume or ultra-low-volume atomizers. These are often based on the spinning disc. In this case it is convenient to use an undiluted formulation. However, whilst it may be possible to use liquid formulations that are intended to be diluted before use, it is more common to use specially formulated products. These are often emulsions, and are frequently oil-based rather than water-based. A formulation's physical properties are then tailored to optimize the performance of their intended atomiser. Within the amenity sector it is very common to add a marker dye to the formulation, so that treated areas are clearly visible. Using undiluted formulations with a high a.i. content can present handling and exposure hazards for the more toxic a.i.s.

Formulations for biological herbicides

Biological herbicides are described in detail in Chapter 19. The same principles that are used for chemical a.i.s apply to the choice of a formulation type for biological a.i.s. High priority is given to creating a safe and stable formulation that is suitable for the chosen application method. However, the use of a living organism makes the challenge more complex!

Tank-mixing different formulations

Formulation design tends to concentrate either on single product use or on a few well-known mixes, mainly because there can be a very large number of possible mixes for some products. However, formulations (and adjuvants) are designed so that they can be freely tank-mixed with a minimum of compatibility problems. Nonetheless, it is important to check the product label for mixes that are not compatible. Some incompatible mixes deactivate some or all of the a.i.s., whilst other incompatible mixes create a gel that blocks the sprayer and takes much cleaning out! It is also important to follow the manufacturer's order for adding products to the spray tank when mixing them. One reason for developing formulations that contain multiple a.i.s has been to reduce the need for tank-mixing.

It has become well known that some products are more effective when tank-mixed with others. There can be a number of reasons. Some a.i.s operate better together because their biological actions complement each other. For example, if a crop is treated with fungicide and herbicide, the crop is made healthier at the same time as weed competition is suppressed, so crop growth may be stronger than if either treatment were conducted on its own. Other a.i.s may have a synergistic action, increasing the level of weed control or broadening the spectrum of weeds that are controlled. Synergistic herbicide mixtures include metsulfuron + CMPP and tribenuron + diflufenican. Alternatively, the liquid properties of the tank mix may enhance a.i. activity above that obtained with the individual products – this is discussed below.

Future trends in formulation

As colloid and surface science continues to develop, so new approaches to formulation will become available. Already, formulations used extensively in other industries such as pharmaceuticals, e.g. microemulsions, mutiple emulsions and controlled release, are spreading to agrochemicals. At the same time, environmental and human health issues make it certain that many chemicals will be phased out, whether replacements exist or not. Future formulations are likely to be heavily water-based, with little use of hydrocarbon solvents. The co-formulants used, especially surfactants, will also change as many are replaced by less environmentally damaging alternatives. For example, nonylphenols are suspected of having endocrine-modulating properties, and so are being phased out in favour of safer alternatives such as alkyl polyglucosides.

The use of controlled-, delayed- and triggered-release formulations is likely to increase, since this offers a way to improve biological performance while simultaneously reducing a.i. dose. The nature of new a.i.s will also strongly influence formulation. If the new a.i.s are less stable to heat, light and water then, clearly, stabilizing them will be the first priority in formulation. Similarly, increased use of biological agents will greatly influence the choice and development of formulation. Also, formulation is strongly influenced by manufacturers' strategy and available processing plant, so the continuing mergers in the agrochemical sector will play a significant part in future formulation choices.

Finally, it should not be forgotten that formulation and application method form an integrated pesticide delivery system, and that both agrochemical and equipment manufacturers can improve the effectiveness of crop protection. Developments in application technology (Chapter 10) and control and decision-support systems (Chapter 15) will have a strong influence on future formulation trends.

Herbicide packaging

The packaging of all pesticides, including adjuvants, has become much more than just using the cheapest practical can or bottle. Packaging is now included in the full 'life-cycle analysis' of a product, and the available packaging options will influence the choice of formulation type. There are numerous legal requirements intended to result in safer product handling and reduced environmental contamination. Nonetheless, manufacturers still adopt a wide range of packaging strategies, using both single-trip and returnable containers, and both open and closed transfer systems.

Herbicide and adjuvant containers must meet a number of requirements:

- they should be made of the most environmentally friendly, ideally biodegradable, materials;
- they must be robust and leak-free during transport and storage;
- their seals and lids should be 'tamper-evident' so that it becomes clear if they have been damaged and the formulation exposed to air which may reduce its shelf-life;
- handling and dispensing the product should be easy, with a minimum of spillage;
- when they are 'empty' a minimum amount of product should be left inside;
- they should be as easy as possible to rinse clean;
- they must carry a clear and legible product label for their whole life.

National and international standards cover all aspects of packaging and containers, defining these requirements in legal form. The product label carries legal and technical information on product use, application and safety precautions. This is increasingly in pictogram form in addition to (or even instead of) text.

Application equipment features are important when considering packaging requirements. For example, the increased provision of induction hoppers and rinsing tanks on boom sprayers has made product dispensing and container rinsing safer.

Open transfer systems

Solid and liquid formulations can be easily measured and added to the spray tank. Where possible, the herbicide should be handled in an area where spills cannot enter the soil and migrate to ground-water. However, much handling has to be done in the field. A well designed container makes dispensing the herbicide easy and safe, e.g. by pouring a liquid product cleanly. Similarly, induction hoppers avoid the need to access the spray tank, which makes dispensing the product easier. In spite of this, powders and dust can be blown away, liquids can splash and any open transfer formulation can be accidentally spilled. Recent studies on isoproturon pollution have shown that the residue left on discarded foil container seals, if allowed onto the ground, can cause equivalent water contamination to that due to drift from the whole day's spraying. Minute splashes of an undiluted product are equivalent to tens or hundreds of litres of spray liquid. Open transfer systems also involve container rinsing which, even with rinsing accessories, is another potential source of pollution due to splashes.

These inherent problems with open transfer systems have led not only to closed transfer systems, but also to the recent development of tablets and bagged products. Tablets, being much larger than granules or powders, hugely reduce dust losses from solid products. They also make measurement of the product into the spray tank easier! Unfortunately, the number of a.i.s suitable for tablet formulations is still small. Bagging can be used for a much wider range of a.i.s, and is the standard method for gel formulations. The bag is made from a polymer which dissolves in water, releasing the product in a few minutes during mixing. Of course, these bags must be kept dry, and are not suitable for water-based formulations. However, they greatly reduce operator contact with the product, reduce splashes and spills and make measurement of the product into the spray tank easier. Bags can also be used to hold incompatible products by adopting the 'bag-in-bag' approach, where each product is in a separate bag, with these bags inside a larger bag. Further development of water-soluble polymers may include impregnating a perforated sheet with the a.i., then simply tearing off strips as required and adding them to the spray tank.

Closed transfer systems

Closed transfer systems are now most common as special containers with couplings that match those fitted to the spray tank or induction hopper. Herbicide is only transferred from the container once a leak-free coupling has been made. A typical transfer rate of 20 litres/min empties a 10-litre container in less than 30 s. These systems can also rinse the container while it is coupled, further reducing potential pollution. The containers may be either single-trip or re-usable, depending on the system used. There are also a few systems where these couplings are used, but the herbicide is pumped from bulk containers. These are more suited to aerial applications than to field use. As yet, there is no 'industry standard' closed transfer system and manufacturers all use their own different systems. Depending on the system used, some types of formulation are not available for closed transfer, generally because of difficulties in emptying the product from the container. In addition, some direct-injection sprayers use closed transfer systems, metering the herbicide from the container as it is required for use on the move.

Disposal of herbicides and packaging

Restrictions on the disposal of unused herbicide and used packaging are becoming ever tighter. In the UK, diluted herbicide can be sprayed off onto unsprayed headlands, subject to not exceeding the label dose, but prior permission from the Environment Agency is required if uncropped land is to be used. For some herbicides, rinsed packaging can still be buried or burned under controlled conditions, although this is not often recommended. Otherwise, a licensed waste disposal site or disposal contractor must be used. Unused products that cannot be returned to a distributor must also go to a licensed disposal contractor. These restrictions make re-usable and returnable containers more attractive to the end-user.

Future trends in packaging

There can be no doubt that packaging will be subject to closer legal regulation in the future, with the aim of improving operator safety and minimising environmental contamination. Open transfer will be discouraged unless in a safer form such as tablets or water-soluble bags, and there will be further development of such 'safe' open transfer methods and formulations. Closed transfer will be more widely used, and will be developed to be suitable for all formulations. With disposal of packaging and unused herbicide entirely through licensed contractors, products are likely to be sold with return of containers to the manufacturer or distributor included in the deal. Re-usable containers will also be more extensively used.

Adjuvants

The exact legal definition of an adjuvant varies from country to country, but may be summarized as:

> 'an approved product that is added to a plant protection product or product mix before application with the intention of improving the plant protection product or product mix's performance.'

Usually the aspect of performance to be improved is the biological activity of the a.i., but this is not always the case. At their recommended use rates, adjuvants can be considered to be biologically inactive.

Adjuvants are used because they have been found to be cost-effective. The extra cost of the adjuvant is usually offset by one of two benefits from its use. There is either a reduction in the amount of herbicide needed, or there is an increase in crop yield or quality. Sometimes both of these benefits apply. However, it is equally true that adjuvants are not a panacea, and should be chosen carefully, after considering which aspect of herbicide performance needs to be improved. With over 200 adjuvants currently available in the UK, this choice can be confusing!

Adjuvant types

Definitions of adjuvants according to their performance or 'mode of action' are often not particularly useful, since the same physical properties that cause one effect can also cause others. For example, a surfactant may have the required physical properties to be a wetter, a sticker, a spreader and a penetrant! So, it is clearer to classify adjuvant behaviour in broad categories. Adjuvants used with herbicides in spray applications are tank-mixed – in the recommended order, of course. The adjuvant then modifies the herbicide's performance in one or more of four broad areas: in the spray tank; during spray formation and transport; during spray deposition; or after spray deposition (Table 9.2). Even these broad areas overlap, as will be described below under 'Effect of liquid properties on herbicide performance'. Most adjuvants change the physical or physicochemical properties of the spray liquid. However, some adjuvants only change the chemical properties; these are the ones which work in the spray tank, e.g. changing or maintaining liquid pH. Note that safeners, which reduce the activity of the a.i. on crop plants and allow higher herbicide doses without increased risk of crop damage, are not always considered to be adjuvants.

Adjuvants may also be divided into broad chemical classes. The major classes are:

- Surfactants
- Emulsifiable mineral, vegetable and methylated vegetable oils

Table 9.2 Adjuvant definitions grouped into broad areas of adjuvant action

Area of action	Definition	Behaviour
Spray tank	activator	increases active ingredient efficacy by changing liquid properties
	acidifier	lowers liquid pH
	buffering agent	causes liquid to resist changes in pH
	compatibility agent	improves liquid homogeneity for tank-mix
	conditioner	reduces water hardness or its effect
	anti-foam agent	prevents foam
	defoaming agent	eliminates existing foam
	foaming agent	creates foam
	colourant	colours liquid
Spray formation and transport	anti-drift agent	reduces spray drift
	anti-evaporant	reduces evaporation during spraying
Spray deposition	deposition agent	improves deposition onto target
	wetter	improves initial impact adhesion of droplets
	spreader	increases droplet spreading on target
Post-deposition	humectant	increases water content and drying time
	extender	increases duration of active ingredient effect
	sticker	increases adhesion and reduces weathering
	UV screening agent	reduces UV light degradation of active ingredient
	penetrator	increases active ingredient penetration into plant
	safener	reduces active ingredient damage to crop

- Polymers
- Polymer- and film-formers
- Phospholipids
- Inorganic salts

Mixtures of these classes, with the aim of combining the beneficial effect of each individual element, are becoming increasingly common.

Surfactants, emulsifiable oils and phospholipids have many of the properties described in Table 9.2. Furthermore, emulsifiable oils and phospholipids contain surfactants to emulsify them into the spray liquid, and so exhibit some of the properties of surfactants. Polymers are most common as anti-drift agents, but are also capable of affecting deposition. Film-formers are extenders or stickers, adding a protective and adhesive layer over the dry deposit. Inorganic salts are activators, modifying the liquid chemistry to enhance a.i. activity on the plant. The effect of adjuvants on liquid properties and a more detailed discussion on their actions are included below under ‘Effect of liquid properties on herbicide performance’.

Adjuvant trends

Adjuvant use is increasing, and with this increase comes the development and use of more complex adjuvants. As reformulating a.i.s becomes more expensive, so there is more scope for using adjuvants to reformulate an old product 'in the tank'. This is particularly true for minor crop uses where it is not cost-effective to optimise a formulation for a particular crop. It is also common for generic products to use very basic formulations whose performance can be considerably enhanced by adjuvants. Even manufacturers who aim to optimise a.i. activity through formulation are adopting the use of 'partner adjuvants', specifically designed to enhance the performance of certain products. Indeed, two distinct formulation strategies have emerged and will continue to be used: either the formulation is intentionally basic and adjuvants are recommended with the product, or the formulation includes 'built-in' adjuvants and is intended not to need additional adjuvants.

Effect of liquid properties on herbicide performance

Spray application of herbicides is very strongly influenced by the physical properties of the spray liquid, in particular the surface tension and viscosity. The density of the spray liquid is always very close to that of water because of the high dilution of the product in water. Liquid properties influence all the stages of spray application:

- Spray formation
- Spray transport and drift
- Deposition and spreading of droplets on plants
- Drying of deposited droplets
- Physical form of the dry deposit
- Penetration of a.i. into the plant
- Translocation of a.i. through the plant

In addition, spray liquid properties affect:

- Compatibility of different products in the spray tank
- Phytotoxicity of co-formulants and adjuvants
- Variation in performance between plant species
- Degradation of the a.i. in soil
- Toxicity of the a.i. to living organisms, including people

How the performance of a herbicide is affected by changes in spray liquid properties depends on the mode of action of its a.i. Active ingredients can be divided into those with contact foliage action, those with translocated foliage action and those with residual action. Contact action herbicides only need the a.i. to be delivered to the weed plant's surface, whereas translocated action herbicides require that the a.i. penetrates the plant tissue. Active ingredients with residual action are applied to the soil, where the a.i. persists to control germinating weeds for some time. Foliage action herbicides are spray-applied, whilst residual action herbicides can be spray- or granule-applied.

In this section each stage of spray application will be considered in turn, including a note of which effects also apply to non-spray, LV (low volume) and ULV (ultra low volume) applications and of cases where particular effects are only applicable to the effect of formulation or adjuvant, rather than both.

Liquid properties in the spray tank

The most important requirement in the spray tank is product compatibility; as noted previously, incompatibilities are given on the product label. Necessary precautions even extend to rinsing the system with a cleaner or a safener-like product after using highly active herbicides such as sulphonylureas. Physically, products must mix well; some co-formulants and adjuvants are used simply to improve mixing. Foam is generally undesirable, and anti-foaming agents are commonly used to avoid foam problems when high surfactant concentrations are present. Mixing incompatibilities, particularly gel formation and particle aggregation or sedimentation, are most common when emulsions are destabilised.

Active ingredients can be degraded by certain chemicals which are (obviously!) not included in their formulation, but may be present in other products. Similarly, some a.i.s are antagonistic to each other and suffer reduced activity when used together. Active ingredients can also be degraded or their activity reduced by changes in the pH or water hardness of the liquid, but the mechanisms of these activity reductions are often not clearly understood. Higher temperatures increase the rate of this degradation. The product label should give information if the product is pH-sensitive. For example, some sulphonylureas may inactivate if left in acidic water for more than a short period. Water hardness problems are linked to the presence of ions associated with dissolved carbonates, sulphates and chlorides of calcium, magnesium, sodium and potassium. For example, calcium and magnesium can reduce the efficacy of glyphosate and 2,4-D. Both co-formulants and adjuvants are used to achieve the correct pH or reduce the effect of water hardness. Equally, the activity of some a.i.s can be increased by inorganic salts; for example, ammonium sulphate or nitrate will enhance the efficacy of glyphosate under some conditions, and can counteract the effect of hard water. Such salts are also added to water-based LV and ULV formulations.

Finally, dirt and organic matter in the water used for dilution can degrade or inactivate some a.i.s: this is probably due to presence of minerals behaving in a similar way to those in hard water. For example, diquat, paraquat and glyphosate can all be affected. Water for dilution should be clean and filtered wherever possible.

Spray formation, transport and drift

Liquid properties are of primary importance in determining the spray characteristics from any atomiser. LV and ULV formulations for use with spinning discs are carefully optimised to produce droplets in the required size range with a given applicator. Spray application is more complex, as a range of atomisers is used:

- Hydraulic nozzles – liquid only
- Air inclusion or venturi nozzles – liquid and air (only liquid pressurized)
- Twin-fluid nozzles – liquid and air (both liquid and air pressurized)

These are descibed in more detail in Chapter 10. Whilst it is difficult to predict droplet sizes in detail there are some useful general rules that can be applied.

Hydraulic nozzles from different manufacturers give broadly similar behaviour. Water-soluble surfactants (e.g. nonylphenols, tallow amines) give the finest sprays and emulsions (whether formulations or adjuvants); dispersible surfactants (e.g. organosilicones), phospholipids and polymers give the coarsest sprays. Where an emulsion is present, addition of water-soluble surfactants makes the spray finer while addition of polymers makes the spray coarser. Addition of another emulsion can make the spray finer or coarser – often, the more surfactant is present in the second emulsion, the more likely the result will be a finer spray.

The difference between the finest and coarsest sprays for a given hydraulic nozzle with different liquids can be up to 20% of the coarsest VMD (volume median diameter; half the spray volume is in smaller droplets than the VMD, half in larger droplets). This is roughly the same effect as doubling the output flow for the nozzle. Polymers, which produce the coarsest sprays, are used as anti-drift agents with hydraulic nozzles. Similarly, legal schemes that classify spray drift use water-soluble surfactant solutions to represent the worst case of spray drift. For example, a LERAP (Local Environmental Risk Assessment for Pesticides) in the UK uses a 0.1% non-ionic wetter solution. Different liquids can also change the patternation of a nozzle.

Venturi nozzles made by different manufacturers can behave differently, in contrast to hydraulic nozzles. However, there are still some general trends, many of which are the reverse of those applying to hydraulic nozzles. Water-soluble surfactants (e.g. nonylphenols, tallow amines) give the coarsest sprays. Emulsions (whether formulations or adjuvants), dispersible surfactants (e.g. organosilicones) and phospholipids give the finest sprays. A number of polymers have been found to cause such an uneven spray pattern that the use of anti-drift agents is not recommended with venturi nozzles. Where an emulsion is present, addition of water-soluble surfactants makes the spray coarser. Addition of another emulsion can make the spray finer or coarser; often, the more surfactant is present in the second emulsion, the more likely the result will be a coarser spray. The reason for this reversal of behaviour in comparison with hydraulic nozzles, while not completely understood, lies at least partly in the inclusion of air within droplets from venturi nozzles. Water-soluble surfactants increase air inclusion, making the toal diameter of droplets increase even though the volume of liquid in them is unchanged. The difference between the finest and coarsest sprays for a given venturi nozzle is greater than that for a hydraulic nozzle with the same liquid output. Similarly, greater differences in nozzle patternation occur for venturi nozzles than for comparable hydraulic nozzles. Again, changes in the spray quality will have implications for spray drift. Twin-fluid nozzles are broadly similar to venturi nozzles, although the control of air flow allows greater control of droplet size.

Liquid properties and spray deposition

Spray deposition is a complex topic, with a large number of interacting variables to consider. There are many excellent descriptions of the processes involved, e.g. in Cottrell (1987), Holloway *et al.* (1994) and Knowles (1998). A simplified overview is given here. The main factors involved in spray deposition are (1) spray quality (i.e. droplet size, speed and number density), (2) liquid properties (especially dynamic surface tension and viscosity), (3) plant surface wettability and (4) canopy density and plant growth habit.

Retention and coverage, while both important, have a different impact on herbicide performance according to the mode of action of the a.i. As a simple rule, retention is more important for translocated action herbicides, where the amount of a.i. on the plant is important for efficacy. Coverage is more important for contact action herbicides, where high surface coverage of the plant is important for efficacy.

Spray deposition is characterised by two measurements: firstly, retention (the amount of liquid retained on the plant) and, secondly, coverage (the percentage of the plant surface covered by the deposit). Coverage can be described by Equation (9.1), where F is a factor to allow for droplets and spreading overlapping on the surface.

$$\text{coverage} = \text{retention} \times \text{liquid spreading on surface} \times F \qquad (9.1)$$

Changes in spray quality affect deposition. Higher spray drift both reduces the total deposition and changes the distribution of deposits within the canopy; high drift is associated with more spray in the top of the canopy. Further, the uniformity of the spray flux under the boom (i.e. the dynamic patternation) varies with spray quality, sprayer forward speed and crosswind. Finer sprays can have less uniform dynamic patternation than coarser sprays, especially on vertical targets. In general, finer sprays are deposited more efficiently on plants than coarser sprays. However, it is only on small targets, and particularly small grass weeds, that the low droplet number density per unit volume of coarse sprays can reduce deposition sufficiently to reduce herbicide efficacy also.

Plant surface wettability plays a key role in retention. If the surface is wettable, then retention is similar for most liquids, and wetter adjuvants offer no benefit.

Droplet spreading is also similar, except where 'superspreading' adjuvants such as organosilicones with EST values below 25 mN/m have been used. In solution, these will spread up to 20 times more than other liquids on wettable surfaces. Spray coverage on wettable surfaces is, thus, also similar for most liquids.

Water-repellent plant surfaces give considerable differences in retention between different liquids (Fig. 9.2). In general, lower DST values correspond to higher retention. The main exceptions to this rule are some polymers, which give higher retention than would be expected from their DST values: these polymers have a 'surface viscosity' which further enhances their retention. Since DST is strongly influenced by surfactant concentration, a very crude rule of thumb is that the higher the surfactant concentration in the spray liquid, the higher the retention on water-repellent plants.

There is a clear hierarchy for retention-enhancing adjuvants on water-repellent plants (Fig. 9.2). Inorganic salts and film formers have little effect on retention. Phospholipids have a larger effect, and are often among the best retention enhancers for emulsion formulations. Emulsifiable oils are generally average to good retention enhancers, but they can also reduce retention when used with emulsion formulations if the emulsions destabilise. While there is often a trend for vegetable and methylated vegetable oils to perform better than mineral oils, this may be due to their containing higher concentrations of emulsifier surfactants. Surfactants are also good retention enhancers, with tallow amines and alkyl polyglucosides being consistently among the best. The data in Fig. 9.2a, with the tallow amine surfactant giving higher retention than the organosilicone surfactant, can be explained by considering the surfactants' DST profiles. The tallow amine is similar to surfactant A in Fig. 9.1, and the organosilicone similar to surfactant B. Although the organosilicone has a lower EST, at the short surface ages applicable to droplet impact it is the tallow amine which has the lower DST, and so gives the higher retention. Indeed, the rate of change of a surfactant's DST profile at medium to short surface ages is one of the best predictors of retention performance (subject to there being no large surface viscosity effects).

It has been shown that, on water-repellent plants, the retention of emulsion-based formulations is the same as the retention of the formulation's emulsifier alone, i.e. the surface tension lowering properties of the surfactants are dominant in determining the retention of emulsion formulations. A similar effect is found with emulsion-based adjuvants. Also, since emulsion formulations already contain surfactants, adjuvants can enhance these products' retention less than they can enhance the retention of water or formulations containing lower concentrations of surfactant. This is illustrated by the data in Fig. 9.2: the best adjuvant gives a six-fold increase in retention on barley plants compared with water, but only gives a two-fold increase in retention compared with a typical emulsifiable concentrate. Note that these increases are for glasshouse-grown plants. Field-grown plants, whose water-repellency has been reduced by damage to their epicuticular wax, might be expected to show increases of about half the magnitude found for glasshouse plants.

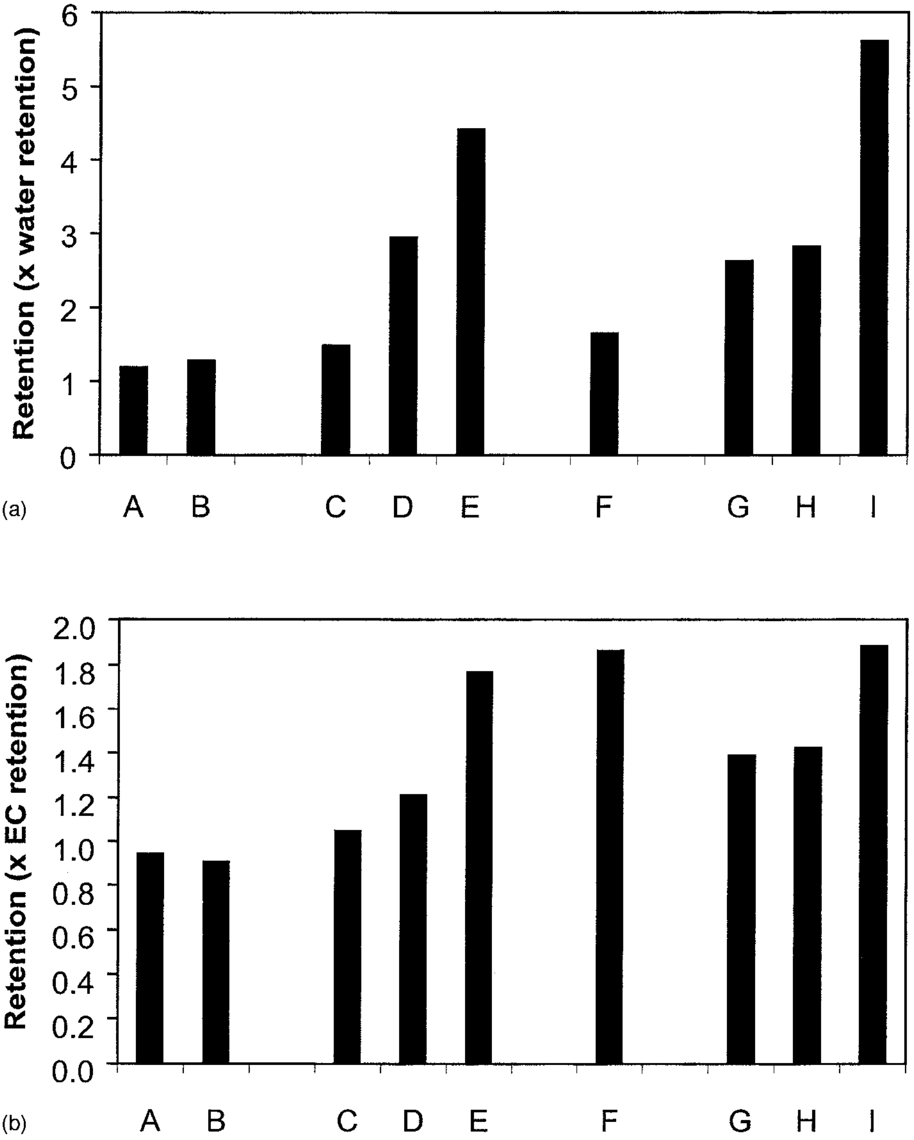


Fig. 9.2 Retention enhancement by adjuvants at full rate on glasshouse-grown barley plants at about growth stage GS 20: (a) for water; (b) for an emulsifiable concentrate formulation. Evenspray FE/80/0.6/3.0 nozzle, ca. 200 l/ha. Adjuvants: A, latex film-former; B, pinolene film-former; C, mineral oil; D, vegetable oil; E, methylated vegetable oil; F, phospholipid; G, organosilicone surfactant; H, nonylphenol surfactant; I, tallow amine surfactant.

This leads to a general conclusion regarding the likelihood of adjuvants enhancing the retention of given herbicides. The higher the surfactant concentration in the spray liquid produced by the herbicide, the better the spray retention on water-repellent weeds. Of course, as previously noted, the type of surfactant present will also influence the level of retention. So, both herbicides with a high a.i. concentration (that need high dilution in the spray tank) and herbicides with low surfactant content are likely to give lower retention, and will be candidates for the use of retention-enhancing adjuvants. The data in Table 9.3 illustrate this point by showing the surfactant concentration in the spray liquid for some typical formulations. Not surprisingly, experiments confirm that similar WDG and SC formulations give lower retention than emulsion formulations, and that their retention is much more greatly enhanced by adjuvants than is the retention of the emulsion formulations.

Table 9.3 Surfactant concentration in the spray liquid for different formulations

Formulation	Formulation contents		Product full rate (g/ha)	Concentration in spray liquid for 100 l/ha	
	a.i. (%)	surfactants (%)		product (g/l)	surfactants (g/l)
Water-dispersible granule	80	1	125	1.25	0.0125
Suspension concentrate	20	5	1000	10	0.5
Emulsifiable concentrate I	48	25	1500	15	3.75
Emulsifiable concentrate II	10	65	2000	20	13
Suspoemulsion	20	40	3000	30	12

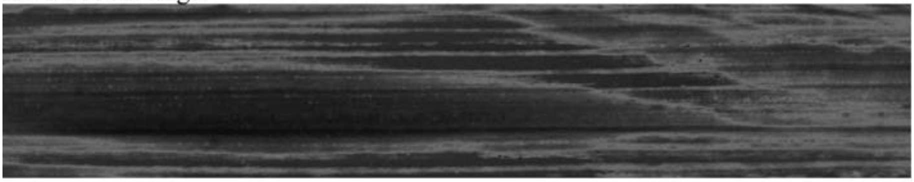
As the crop becomes taller and denser, so these differences in retention are reduced. Put simply, droplets cannot avoid the foliage, and even if they bounce off at the first few impacts they will still be retained lower down in the crop. Thus, total retention becomes similar for different liquids, even for water-repellent plants. However, spray quality and liquid properties still influence the distribution of deposits within the crop. Water, and other poorly retained liquids, give similar deposits in the top and bottom of the crop, but the well retained surfactants often give higher deposits in the top of the crop than in the bottom. This partitioning has significant implications for herbicide efficacy, particularly if the weed is smaller than the crop. Coarser sprays and higher application volumes will often increase deposition lower in the crop.

Droplet spreading on water-repellent surfaces also changes with different liquids. In general, since spreading is a slow process, it is the EST or long surface age DST values which influence how much a liquid will spread. Lower EST and long surface age DST values correspond to higher spreading. Returning to the tallow amine and organosilicone surfactants (similar to A and B, repectively, in

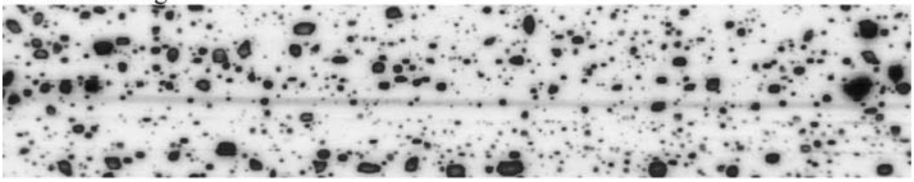
Fig. 9.1), the EST and long surface age DST values predict that the organosilicone, with lower EST, will spread more than the tallow amine. This is the case; the organosilicone spreads around 20 times as much as the tallow amine.

Spray coverage depends on both retention and droplet spreading and changes with different liquids on water-repellent surfaces. The lowest coverage is given by water, which combines low retention with minimal spreading. Organosilicones, whose very high spreading compensates for their average retention, give the highest coverage. Figure 9.3 illustrates spray coverage effects for three surfactants on barley leaves. The organosilicone (EST 22 mN/m) gives above 90% coverage, the nonylphenol (EST 30 mN/m) gives around 40% and the tallow amine (EST 41 mN/m) gives around 30%. Interestingly, their ranking order for coverage is the opposite to that for retention.

A > 90 % coverage



B 40 % coverage



C 30 % coverage

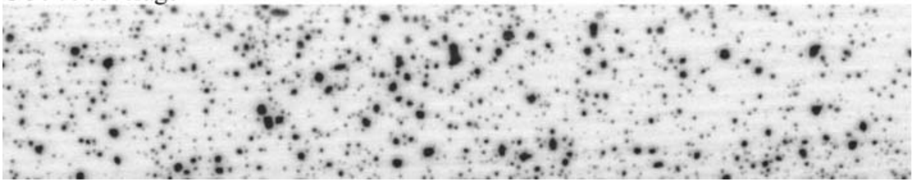
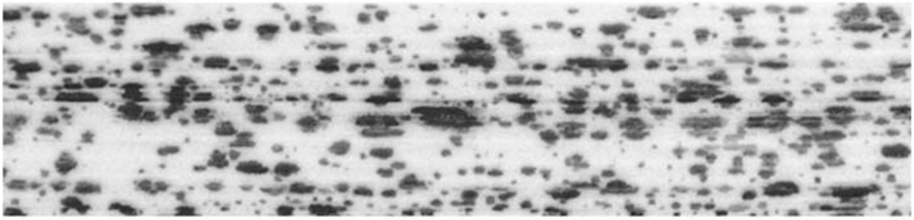


Fig. 9.3 Spray coverage of barley leaves ca GS 20. Evenspray FE/80/0.6/3.0 nozzle, ca 200 l/ha. (A) Organosilicone surfactant, 1.5 g/l; (B) nonylphenol surfactant, 1 g/l; (C) tallow amine surfactant, 5 g/l. Each figure 1 cm high.

Repeating a theme from retention behaviour, the surfactants in emulsion-based formulations and adjuvants strongly influence droplet spreading and spray coverage. Figure 9.4 illustrates the influence of surfactant concentration in the spray liquid on spray coverage of barley leaves. The methylated vegetable oil (coverage around 36%) has five times the surfactant concentration of the vegetable

A 36% coverage



B 13% coverage

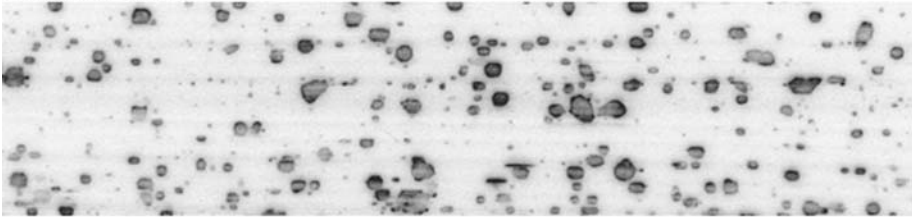


Fig. 9.4 Spray coverage of barley leaves ca GS 20. Evenspray FE/80/0.6/3.0 nozzle, ca 200 l/ha. (A) Emulsifiable methylated vegetable oil, 10 g/l; (B) emulsifiable vegetable oil, 10 g/l. Each figure 1 cm high.

oil (coverage around 13%). Here, both retention and coverage are higher for the methylated vegetable oil. So, as for retention enhancers, a formulation's need for coverage-enhancing adjuvants can be roughly predicted from its surfactant concentration in the spray tank (as given, for example, in Table 9.3).

Drying and the form of deposits

After the spray liquid has spread on the weed surface in the seconds immediately after deposition, longer-term drying and spreading effects occur. As the droplet dries, so its liquid properties change. Generally, water and solvents evaporate and the concentration of a.i.s, oils and surfactants in the deposit increases. This may result in slow secondary spreading of the drying deposits, and can influence the uptake of translocated a.i.s, which takes place before the a.i. solidifies. The drying process is very complex because of these time-varying concentration effects. For example, it has been observed that the presence of different surfactants results in dried deposits being located at different points on the external plant surface cells. Active ingredients may also evaporate, but vapour action is generally undesirable for herbicides because its uncontrolled nature can result in off-target damage, so formulation usually aims to minimize a.i. evaporation.

Penetration of a.i. into the plant

Penetration into plant tissues is a very complex area with an extensive published literature, and there are still intense debates over the exact mechanisms involved. In the simplest terms, appropriate surfactants will enhance the uptake of most translocated herbicides. The optimum surfactant for a given herbicide depends on the nature of the a.i. Less ethoxylated surfactants with lower hydrophile–lipophile balances are best for lipophilic (oil-soluble) a.i.s, whereas water-soluble a.i.s favour highly ethoxylated surfactants with higher hydrophile–lipophile balances. Oil-based adjuvants, and emulsions containing oils, also enhance uptake, with the surfactants and oils both playing a part in this enhancement. Some polymers will also enhance uptake. Generally, co-formulants and adjuvants do not appear to modify translocation directly. Rather, increased a.i. translocation is the result of increased a.i. uptake.

Penetration into the internal plant tissues can occur through the cuticle and epidermis (the plant's 'skin') or through the stomata (the plant's 'pores'). Most surfactants and oils penetrate the cuticle and epidermis when enhancing a.i. uptake, though at very different rates and to different depths. Organosilicones, however, can induce very rapid a.i. uptake via the stomata, almost certainly as a result of their very low ESTs. For the a.i. to penetrate the cuticle and epidermis, it must be in a liquid form. So, to increase the total amount of a.i. taken up, either the rate of uptake must be increased or the period for which the a.i. remains in liquid form must be lengthened (or, ideally, both). Hence has come the use of humectants which extend the duration of the liquid phase of the deposit. Similarly, film-formers not only increase rainfastness, but also reduce evaporation from the deposit. Enhanced a.i. uptake results from highly concentrated oils or surfactants in the drying deposit either solubilising the a.i. or acting as solvents for it. The uptake of many a.i.s increases with a.i. concentration per unit area. This is probably related to the a.i. concentration gradients that exist within the plant cells during uptake.

There are many models of the uptake processes that seek to predict rates of diffusion and the effect of uptake on translocation. Some models use realistic plant structures, others use more schematic mathematical descriptions of the plant. Whichever model is used, simulations are now able to predict a.i. transport for some situations. A good example (albeit for a fungicide) is given in Fig. 9.5, where the simulation corresponds almost exactly with a.i. behaviour in a leaf (Cox *et al.* 2000). This simulation divides the leaf into a cuticle, a sorption layer and an internal layer with translocation. One of the more useful principles from these models is to regard uptake enhancement as having two distinct elements. One element is the solvent or solubilising property, which keeps the a.i. in a suitable form for uptake but does not directly affect the rate of uptake. The other element is an accelerating or activating property, which does increase the rate of a.i. uptake. Thus, the best uptake enhancers would be regarded as having both of these properties.

Efficacy enhancement

The enhancement of herbicide efficacy by an adjuvant (or co-formulant) can be described by Equation (9.2).

$$\text{efficacy enhancement} = \text{deposition enhancement} \times \text{a.i. activity} \qquad (9.2)$$

This means that, however good the increase in deposition, if an adjuvant or co-formulant inhibits the biological activity of the a.i. then total herbicide efficacy will be reduced. For example, using a less ethoxylated surfactant with a water-soluble translocated a.i. such as glyphosate results in a total loss of efficacy in spite of significantly increased foliar retention, because the surfactant reduces uptake of the a.i. to almost zero. Similarly, tallow amine surfactants are often

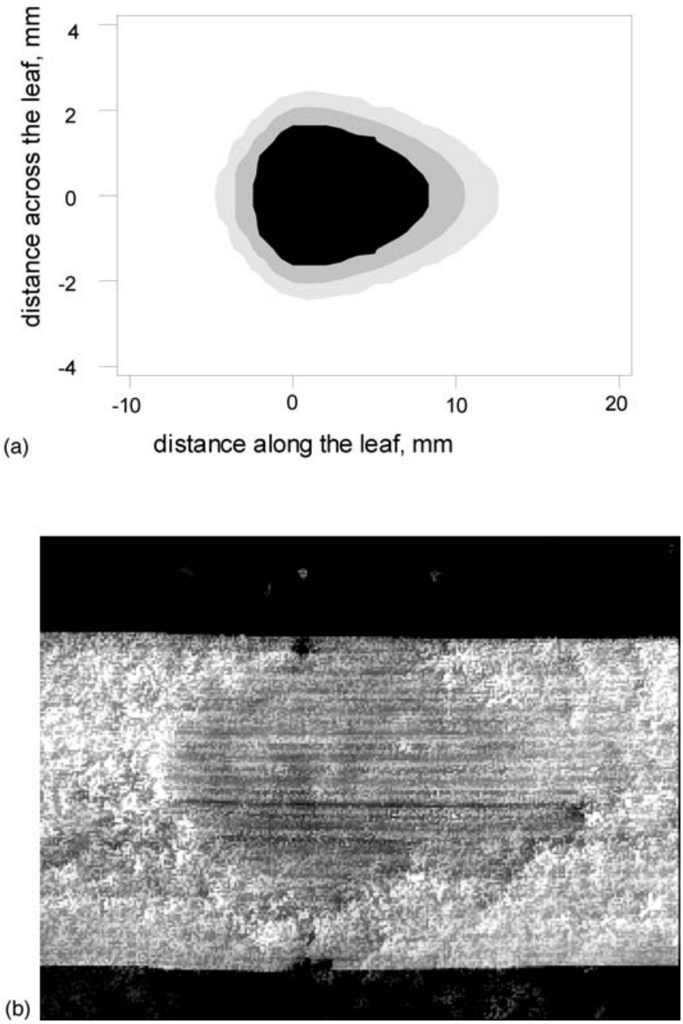


Fig. 9.5 Diffusion model for pesticide transport on a leaf after 72 h. (a) Simulation model; application point (0, 0); transport left to right. (b) Fluquinconazole, 0.5% w/v on barley leaf. (*Courtesy of Dr. David Salt, School of Computer Science and Mathematics, University of Portsmouth.*)

used in glyphosate formulations because they combine high retention with low droplet spreading to give fewer, more concentrated deposits (e.g. Fig. 9.3C). Not only is more a.i. available on the weed, but it is in a form of deposit which increases uptake. Thus, efficacy is considerably enhanced by the tallow amine.

Phytotoxicity

Although it is convenient to regard adjuvants (and co-formulants) as biologically inactive, it is not entirely correct. Many surfactants, solvents and oils are phytotoxic, but only at higher concentrations than are found in the spray liquid. However, as described in the previous section, the drying deposit contains much higher concentrations of these materials than the spray liquid, and phytotoxic effects are sometimes observed.

The most common problem causing damage to the crop is not really phytotoxicity. It is the creation of a 'hot' mix whereby a herbicide's efficacy is sufficiently increased by other products or adjuvants in a tank-mix for it to damage the crop. Whereas most 'hot' mixes are known and can be avoided, new products and adjuvants will occasionally result in new 'hot' mixes.

Conclusions

Increased understanding of the physical and chemical processes involved in the different stages of herbicide delivery has resulted in significant improvements to the safety and efficacy of herbicide formulations. There are now many more formulation options to choose from when seeking to unlock the full activity of herbicides, including an ever-increasing range of adjuvants. It is important that future development continues to take a holistic approach, and in particular includes application technologies. There are many formulation methods used elsewhere in industry that may be suitable for herbicides, especially with respect to meeting demands for increased safety and reduced environmental contamination. Finally, when considering the scale of the challenges that lie ahead, it is worth remembering that even the best herbicide delivery systems currently succeed in delivering less than 30% of the a.i. to its biological target site.

Key points

- Formulation and packaging are an integral part of the total delivery system for a herbicide.
- The main emphasis in herbicide delivery is now on increasing safety and reducing environmental contamination, ideally including a decrease in the amount of a.i. use.
- When choosing the formulation type for a herbicide, it is important to consider its effect on the application process.

- Formulation components and adjuvants influence all aspects of pesticide application, from spray generation to uptake of the active ingredient.
- For deposition, spray droplet size is only of major importance on small targets such as young grass weeds, when an excessively coarse spray will give unacceptably low deposition and reduce herbicide efficacy.
- The wettability of the weed surface determines whether there will be differential retention and coverage for different liquids: water-repellent surfaces give large differences, wettable surfaces little or no difference.
- Surfactants dominate the physical processes involved in retention, spreading and coverage.
- Translocated herbicides are only taken up into the plant tissues if the a.i. is still in a liquid form.
- However efficiently a herbicide is deposited onto a weed, efficacy depends on the a.i. moving from the deposit to the point of biological action.
- Herbicide delivery still utilises less than 30% of the a.i. applied, so there is great potential for further improvements in its efficiency and effectiveness.

Acknowledgements

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Chapter 10
Methodology of Application

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Objectives of the operator

Optimising the application of a herbicide can make the difference between achieving good weed control and apparent failure to control weeds with a product. The way in which a herbicide is manufactured, tested and supplied is meticulously monitored by the manufacturer and the registration authorities right up to the time when it is delivered to the end-user, at which point the success or failure of that herbicide depends upon the quality of its application.

The spray operator is responsible for the fate of the herbicide. For safety and effectiveness it must be applied at the correct dose of product in the recommended volume of liquid at the recommended spray quality, at the optimum time. This must be carried out with the minimum risk of contamination to the operator, the environment and the general public. Following the application of a pesticide, the spraying machinery and protective clothing must be decontaminated in a safe and effective manner.

The importance of the sprayer operator to the general public's perception of agrochemicals and spraying cannot be over-emphasised. Of all the activities from the initial development of a herbicide onwards, it is the actions of the operator before, during and after applying the product which the general public is most likely to observe at first hand.

The principles of herbicide application are the same for all types of herbicide formulation and application equipment. The operator is trying to apply the correct quantity of product per unit area of ground evenly in the most acceptable manner to produce effective weed control with the minimum off-target wastage. Due to the similarity of the principles, aspects such as calibration and maintenance apply equally to all types of sprayer, from the largest self-propelled machine to the smallest knapsack, and even to band sprayers and granule spreaders.

Interpreting the label

It is mandatory to include the following instructions on herbicide labels:

- Field of use (e.g. whether the product is for use within broad categories such as agriculture, horticulture, home garden, etc.)

- The crops, plants or surfaces on which the product may be used
- The maximum dose rate
- The maximum number of treatments
- The latest time of application
- Any limitation on area or quantity allowed to be treated
- Any statements about operator protection or requirements for operator training
- Any statements about environmental protection

There may also be specific prohibitions relating to individual products which will need to be obeyed. Any breach of these or the other statutory conditions of approval relating to use will constitute a criminal offence.

A herbicide product label should always be read thoroughly before the product is bought or used. Labels also carry other advisory information which users are encouraged to follow to obtain the best results.

Hydraulic ground-crop sprayers

Preparation

Preparation of the sprayer commences at the end of the previous season when the machine is put into storage. It should have been triple-rinsed internally using washing soda on the second rinse, and finally flushed through with a small quantity of 30% anti-freeze. The outside of the sprayer must be washed down thoroughly and notes made of any faults or alterations that require attention before the new season. Nozzles and diaphragm check valves (DCVs) should be removed and stored in the filter basket. A sufficient time before starting the new season's spraying, various checks should be carried out:

- Re-assemble all sprayer components
- Check chassis, tyres and wheels, and boom for wear and damage; repair as necessary
- Check that the p.t.o. is of the correct length for the tractor/sprayer combination and that the guard is intact and secure
- Check condition of all wearing parts on the sprayer and lubricate according to the manufacturer's recommendations
- Check tank for security of mounting
- Dismantle filters and check for cleanliness and condition; replace all 'O' rings to avoid leakage problems in season
- Check the oil level in the pump and make sure the oil does not contain water, which would turn the oil milky and indicates a diaphragm failure; on grease-lubricated diaphragm pumps, diaphragm failure is signalled by water pouring out of the bottom of the pump
- Check that the pressure gauge returns to zero and is undamaged

- Fill the sprayer with water
- Run the sprayer at normal p.t.o. speed and with all nozzles spraying increase the pressure to 5 bar – if the pressure will not reach 5 bar there is either an air leak in the suction system, or the pump is defective (see Table 10.2); this test does not apply to centrifugal pumps which are unable to attain a pressure greater than 3 bar
- Re-set the pressure to the expected operating pressure, which is normally in the range of 2–3 bar, and check the spray for pulsation
- If the spray pulsates, adjust the air pressure in the pump pulsation damper; follow the manufacturer's instructions, but generally a pressure of 2 bar is recommended
- The capacity of the damper chamber is very small so it must be filled by a hand pump or a foot pump; an industrial compressor is too harsh and may damage it
- Check that all the switch gear operates as intended, and that bypasses for individual boom sections are correctly adjusted so that the pressure remains constant when individual boom sections are switched off; if nozzles drip when the boom is turned off, the diaphragm check valves require servicing
- Remove the tank lid and check that the vent is not blocked
- Check that no air bubbles are circulating in the tank; air bubbles indicate an air leak on the suction side of the system

When all checks are complete and everything is working as the manufacturer intended, the sprayer is ready for calibration. However, it is worth emphasising that many problems associated with sprayers during the spraying season stem from over-tightening of plastic components. Virtually all plastic components such as DCVs and filters should only be moderately hand-tightened. Over-tightening invariably leads to leakages and frequently causes damage to the components. An over-tightened DCV can also restrict the flow of liquid to that nozzle.

Atomizers and nozzle types

Flat fan nozzles – 110° and 80°

Fan nozzles are the most widely used in agriculture. Their virtue is that they have a mixed spectrum of droplet size which allows the delivery of an effective dose to a wide range of targets when running between 2 and 4 bar, and when operated with the correct overlap, produce a uniform distribution across the ground. There is a preference for 110° nozzles, as they can be carried closer to the crop, and are less sensitive to boom roll.

Extended range fan tips – TeeJet XR, Lurmark VP

Similarly to a traditional flat fan, the orifice is machined narrower across its width, and wider along its length. The shape of the orifice means these nozzles produce a finer spray than the conventional flat fan, and are capable of running at reduced pressure without the fan pattern collapsing. Extended-range nozzles are particularly good for graminicide applications.

Hollow cone nozzles

Hollow cone nozzles produce a finer spray quality than fan jets at like pressures. They also produce a less even distribution and are more sensitive to boom height variations. A cone jet places approximately three times more spray at the edge of its pattern than in the centre. Hollow cones are a poor choice for herbicide applications, as they produce an uneven distribution across the width of the boom when compared with fan jets. However, they can be useful for low-volume applications, as they are less prone to blockage, and it is argued that for some band spraying tasks the uneven distribution is a benefit (see 'Band sprayers' section).

Pre-orifice (low-drift) fans – 110°

Low-drift nozzles are designed to work within the 2–4 bar pressure range but produce significantly less drift than a conventional fan tip. They actually operate at a relatively low tip pressure because the liquid is forced through a small pre-orifice which drops the pressure before the tip. Typically they produce a coarser spray, and about half as much drift as an equivalent conventional fan jet. Their performance is similar to a low-pressure nozzle; Novartis trials have proven these tips work well with cereal fungicides and with autumn residual herbicides.

Low-pressure nozzles – 110° and 80°

Low-pressure nozzles are designed to give large drift-reducing droplets when working at pressures between 1 and 2 bar. The relatively large droplets are good for soil-acting herbicides. Low-pressure nozzles are slightly less prone to blockage than pre-orifice nozzles. Operators must be careful that DCVs operate correctly at the low pressures associated with these nozzles.

Deflector nozzles – Turbo TeeJet

These nozzles produce a coarse spray, with a very uniform distribution. They are very resistant to clogging even for small orifice sizes. They are good for soil-acting herbicides. Low-pressure, deflector and low-drift nozzles have been largely superseded by the air induction nozzle.

Air induction nozzles – Billericay Farm Services Bubble Jet – 110°

Significant reduction in drift is obtained with the new generation of air induction nozzles. Spray passing through the nozzle tip sucks air in through a venturi hole and mixes it with the spray liquid to produce air-filled droplets. The drops are much larger than those produced by a conventional fan jet. Currently there is no classification system for the air-filled drops. Where drift avoidance is of paramount importance, these are the hydraulic nozzles of choice, typically reducing drift by between five- and nine-fold compared with the conventional flat fan.

Twin-outlet cap and twin orifice nozzle tips

A twin outlet nozzle tip or two half-rate tips in one specially designed bayonet cap gives a spray quality finer than that from a single tip working at an equivalent application rate, while the fore and aft angling of the outlets results in better penetration of the spray into broadleaved crops. For herbicide applications, the key use for these nozzles is in cases where the label requires a high water volume combined with a medium- or fine-quality spray. By choosing appropriate nozzles one can also travel at higher speed while applying a high water volume at a normal spray pressure and quality.

Twin fluid atomisers – Airtec and AirJet Sprayers

Spray-mix under pressure is mixed with air under pressure in a specially designed nozzle with a large orifice which tends to reduce blockages. By altering the balance between liquid and air pressure, an operator can adjust the spray quality while maintaining application rate. Airtec users like to operate at volumes between 70 and 100 l/ha. With a few exceptions (Swipe™ and Fubol™), Novartis products perform as consistently through Airtecs as through conventional equipment. The Airtec has two advantages to the farmer: high work rates, and reduced drift capability on the move. One needs to be aware that there is a temptation for operators to coarsen the spray to reduce drift, which may lead to reduced efficacy. Airtec sprayers produce less drift for a given spray quality than conventional flat fan jets.

Sleeve boom sprayers – Degania, Rau, Hardi Twin

Generally products are more effective when applied through these machines than through conventional sprayers. For best effect a fine spray needs to be applied. The principle is to entrain the spray in the air, and to replace the air in the crop with air from the sprayer, thus reaching all the vegetation in the crop. Once the balance of crop volume, air output, boom height and forward speed is correct, excellent results will be obtained with these machines. Where problems arise it is because the operator has a poor understanding of the machinery and its principles. Usually this involves the use of too much air, leading to excessive spray drift, and sometimes inefficacy and crop scorch. The greatest risk of drift is when crop cover is minimal. Operators of these machines need to be motivated and well trained.

Direct chemical injection

Most sprayers apply a mix of chemicals and water, mixed in the tank. Some sprayers, however, keep the chemical and the water separate. The chemical is metered into the water just before it leaves the nozzle. The main advantages of this type of system are that the spray tank contains only clean water, so in principle the machine is easy to clean out. One can also vary the rate of product application according to requirements.

Spray monitors and controllers

A spray monitor is essential for safe and effective spraying on larger farm units. Most monitors are used for adjusting nozzle outputs to maintain a constant application rate, should speed vary. They also have significant benefits in other aspects of spraying. A top-quality spray monitor will measure sprayed area and tank contents. These features enable operators to finish a spray programme without having to dispose of any waste spray. They can also store application records, enabling the operator to download them at the end of the day.

Water volumes

Traditionally much UK spraying has been done at 200 l/ha and most of the initial trial work on new products is still carried out at this rate using flat fan nozzles. Where high levels of penetration are required in dense crops, a higher volume may be recommended at anything up to 1000 l/ha; conversely some products have a lowest permitted volume in order to safeguard efficacy and crop or operator safety.

How much can they be reduced?

Potential spraying time is often wasted during travelling and refilling, so sensible water volume reduction is one of the biggest contributors to productivity, more timely spraying and as a result better product performance. Many products perform well at reduced volumes, but the manufacturer may not have done the necessary work to support a reduced-volume recommendation. Advice should be obtained when a minimum volume is not given on the label. This may be available from the manufacturer, distributor, consultant or farmer trial group (see also Chapter 16). But remember that a manufacturer may not support such a recommendation if it is outside the label information or their subsequent advice.

The use of twin-fluid air injection nozzles as found on an Airtec or AirJet sprayer and the use of air-assisted sleeve boom sprayers is often associated with reductions in application volume, down to about 70 l/ha, giving operators the advantage of very high work rates. Trials have shown that reduced volumes generally result in increased spray retention on the target. This may or may not result in improved performance of the product, as product performance may also depend on coverage and concentration of the product.

Advantages and risks of water volume reduction

The time saving with reduced water volumes (implying more hectares/day = more timely spraying) frequently improves efficacy. It can make the difference between optimum timing, and missed opportunity. However, a reduced water volume may make the spray ‘hotter’ when a plant is under stress or we have the wrong sort of weather. Where a high degree of coverage is known to be necessary, such as with a contact herbicide, efficacy may be reduced.

Table 10.1 Legal constraints on reduced-volume application

Label prohibits reduced-volume spraying at recommended dose, or has maximum statutory concentration. Product is classified as: Very Toxic, Toxic, Corrosive, Risk of serious damage to eyes. Label requires use of ppe* when pesticide is diluted to the minimum volume rate at the recommended dose.	Reduced volume allowed as long as maximum concentration recommended on the label is not exceeded. Reduce product dose in line with reduction in water volume, e.g. half the water volume permits half the dose rate.
All other products	Full dose can be used at up to 10 times the permitted concentration.

* ppe, personal protective equipment

The legal constraints on reduced volume application are shown in Table 10.1.

Calibration

The operator must first read the product label for information specifying spray volumes, forward speed, nozzle type, spray quality and operating pressure. When all this information is given, the operator's task is simple: he or she must fit the recommended size and type of nozzle, and calibrate for the recommended forward speed and nozzle output. Where less information is given, e.g. only the spray volume range, the operator must work from basic principles.

Choosing spray volume rate

The volume rate on the label is recommended in litres of water per hectare, with lower and upper limits. The volume rate must be chosen within that range, taking into account any other information on the label and previous experience. It should be borne in mind that the lowest recommended volume rate will give the highest work rate, that the maximum capacity of the pump might limit work rate and that certain crop situations such as a dense canopy may require the higher end of the volume range.

Measuring speed

The operator should carry out a trial run to establish a forward speed which gives an acceptable level of boom bounce and yaw, and a gear which gives a p.t.o. speed of about 540 rev/min. From a speed check over 100 m, using the gear and rev/min as above, the time taken, in seconds, to cover this distance is measured; then one can calculate the speed from Equation (10.1)

$$\text{speed (km/h)} = 360 \times \text{time} \tag{10.1}$$

Calculating nozzle output

The nozzle spacing is measured and recorded in metres, the output per nozzle required to achieve the intended volume of application is thus established from Equation (10.2), and recorded.

$$\underset{(\mathrm{l/min})}{\text{nozzle output}} = \underset{(\mathrm{l/ha})}{\text{volume of application}} \times \underset{(\mathrm{km/h})}{\text{speed}} \times \underset{(\mathrm{m})}{\text{nozzle spacing}} \times 600 \qquad (10.2)$$

Selecting nozzles

By referring to the nozzle manufacturers' data charts or cards, or the BCPC *Nozzle Selection Handbook*, the type and size of nozzle is selected which will provide the calculated nozzle output and the spray quality required. The pressure is set to the recommended level.

Checking nozzles

The nozzles are fitted and the spray patterns and alignment are checked visually; any rogue nozzles are replaced. The outputs of individual nozzles are compared by use of a measuring cylinder; and any nozzles with more than 5% variation from the average are replaced. Nozzle manufacturing quality has improved to the extent that a new set of nozzles should vary in output by less than 1%.

Calibrating the sprayer

Using a calibrated vessel, the output from four nozzles, at least one from each boom section, is measured and compared with the calculated nozzle output. If the output of these four nozzles differs by a small amount from the calculated output, the pressure is adjusted and the calibration is repeated. If the output differs by a large amount, the calibration and the calculations are re-checked and the nozzle size is changed if necessary.

Calculating the doses

Pesticides are formulated as either solids or liquids (Chapter 9) and their doses are specified as kg/ha or l/ha of the formulated product. Where possible, chemical manufacturers package their products in unit area packs, usually of 1 or 2 ha, to simplify the job of measuring the correct quantity of pesticide into the spray tank and to reduce the risk of errors. However, this is not always possible, particularly when a product has several recommended doses. Larger packs of 20–600 l are also becoming more common, as they help to reduce the burden of packaging waste on the environment.

The quantity of product to be required per load is calculated by dividing the tank capacity (litres) by the application rate (l/ha) and multiplying the resulting figure by the dose rate (l/ha or kg/ha). For example, if the tank capacity is 2000 l and the application rate is 100 l/ha, then the area treated per load is 2000/100 = 20 ha. If the dose rate is 0.125 l/ha, then the quantity of herbicide required for each tank load will be 20 × 0.125 = 2.5 l. If only a part-load is required, the quantity of pesticide added must be proportionately less.

Mixing the product

Whether filling the sprayer direct or from a pre-mix tank, the correct procedure should be followed. Before starting the operator should be wearing the protective clothing stated on the label. The biggest source of environmental contamination from spraying is spillages at the filling site. Spillages are most easily avoided by taking care not to overfill. Precautions include ensuring only to fill the sprayer to 90% of its capacity. In addition the operator should use a flow meter to measure in the required amount of water accurately, and should place a drip tray under the induction hopper to catch any inadvertent spillage. It is essential to read the label before opening the chemical container, and to follow the recommended mixing procedure. The operator must ensure that weather, field, and crop conditions comply with the instructions for use and safe spraying practice.

When mixing products, approved products and tank mixes only should be used. When applying tank mixes, particular attention should be paid to the order of mixing of the components.

The correct procedure is first to part-fill the sprayer with water. Some products, such as water-soluble bags, require a minimal amount of water in the sprayer for maximum agitation, whereas others require almost the maximum amount of water for the greatest possible dilution. Then the pump is started and the operator checks that the agitation is working correctly. Next the calculated amount of products is measured into the sprayer, using a low-level induction hopper to avoid risk from glugging and splashing. Each product should be added separately to the sprayer tank and allowed to disperse completely before adding the next product. The tap should be closed immediately after the last of the product has left the hopper, or air may be sucked into the spray mix, causing foaming. Then the containers should be washed out with clean water. Agitation is continued while the remainder of the water is added to the required amount. Creation of excess frothing by over-agitation should be avoided. Any spilt pesticides must be washed off the sprayer and containers, and what has collected in the drip tray should be added to the spray mix. Spilt pesticides must be washed off impermeable clothing such as gloves, boots, apron and face shield. All used and unused pesticide containers must be closed, and stored in a secure place to prevent theft, misuse or contamination. Before getting into the tractor cab the operator should remove any protective clothing not required by law except boots and coveralls, and store them in the tractor locker, not inside the cab.

Field procedure

Accurate marking out is a pre-requisite to accurate spraying. Commonly used marking systems include tramlining with the drill, foam marking and flags.

Tramlining with the drill is the most accurate and convenient system, providing the drilling is done accurately in the first instance. Foam markers are particularly useful for pre-emergence sprays, but are less reliable than tramlines, and they are an extra factor on which the sprayer operator must concentrate while driving. This is particularly a problem with wide boom sprayers. Portable flags are the least preferred method as they are time-consuming to set up accurately and impossible to see when the field has a rise in the middle. With the advent of (GPS) the latest system for bout marking is a light bar. The light bar is mounted on the dash of the tractor, and receives signals from satellites to obtain its position. The operator looks at an array of lights, which move left or right as he veers off course. By keeping the light in the centre of the light bar, the operator will be driving to a deviation of less than 0.5 m.

It is good practice to allow two headland bout widths with a 12 m sprayer. Sprayers of 18 m boom width and above generally only need one bout width around the headland. The headland should be drilled to the same width as the sprayer headland, as the change in direction of the crop rows signals the sprayer operator when to turn on and off. Where large obstructions such as ponds or pits exist in the middle of a field, they should be drilled around and sprayed around as separate headland.

On entering the field to be sprayed the operator's first task is to set the nozzles to the correct height above the crop. Having purged the spray line of air and water, the operator sprays out the headlands. At the corners the operator must stop spraying a bout width away from the edge of the field, reverse back into the corner, then spray down the next field edge. This manoeuvre squares off the corner and avoids the localised under- and over-dosing associated with spraying round corners, during which the faster-moving outside boom underdoses while the slower-moving inside boom overdoses. Outside corners should be squared off in a similar manner.

Having sprayed the headland, the sprayer should work up and down parallel to the longest side of the field, or follow the drill rows if these are different. Large obstructions have already been dealt with. Small obstructions such as trees and telegraph poles require a different approach. A sprayer cannot be sprayed round a telegraph pole without encountering the same under- and over-dosing problems associated with spraying round corners. A hydraulic folding sprayer should be driven right up to the telegraph pole stop, then the operator should reverse back, fold in the boom, drive past the pole, unfold the boom, reverse back to the pole and then continue spraying. The same procedure applies for manual folding booms except that the tractor has to make a wider loop to negotiate the telegraph pole and consequently damages more crop.

It is important to maintain a constant speed when spraying, whether using a basic field crop sprayer or even one fitted with an automatic spray regulating system. The basic sprayer relies on accurate maintenance of the forward speed and pressure for an accurate application rate. Although automatic spray regulating devices compensate for an increase in forward speed by increasing the operating pressure to maintain a constant application rate, of course increasing the pressure reduces the droplet size of the spray, resulting in an increase in drift. This effect is more serious than is frequently perceived. A doubling of the forward speed requires a four-fold increase in pressure at the nozzle to maintain a constant application rate. For example, a sprayer working at 3 bar pressure and 8 km/h would require an operating pressure of 12 bar to maintain the same application rate at 16 km/h. The resulting increase in drift would be totally unacceptable and might lead to crop damage and poor weed control as well.

There are further points to watch when spraying. The operator should ensure he or she does not run out of spray half-way across the field. With modern spray monitors, one can record the size of the field, the lengths of the tramlines and the amount of spray-mix applied, so running out of spray is unlikely providing the monitor is used to its full capabilities. It is important to keep a regular check on the nozzles while spraying and always to carry spare nozzles as replacements. For obvious health and safety reasons, one should not blow through nozzles to clean them. Whenever one is changing nozzles, the required protective clothing for handling the concentrate must be worn. It is useful to have on hand during spraying an adequate supply of clean water, soap, a towel, a suitable First Aid kit and a spare pair of protective gloves.

Rotary atomizers

Preparation

The preparation of the rotary atomiser sprayer is essentially the same as for the hydraulic ground crop sprayer except for the nozzles, which are replaced by the rotary atomiser heads. The drop size is dependent on flow rate of liquid to the head and rotational speed of the head. The uniformity of flow to the individual heads is easily checked using water. The rotational speed of the discs must be checked with a rev counter.

Rotary atomiser sprayers are generally associated with very low liquid flows and concentrated spray mixtures. They are much more prone to blockages than a hydraulic ground crop sprayer. The operator frequently cannot see the heads working from his position in the cab, so a blockage may go unnoticed for a considerable period of time. Good filtration and meticulous sprayer hygiene cannot be overstressed for this type of equipment.

Testing and checking

First, the label should be read and checked for recommended volume of application and drop size. Next a trial run is carried out to establish a forward speed which gives an acceptable level of boom bounce and yaw, and a gear which gives a power take-off (p.t.o.) speed of about 540 rev/min. From a speed check over

100 m, using the gear and rev/min as above, the time taken in seconds to cover this distance is measured and the forward speed is established from Equation (10.1) given previously.

Calculating atomiser output

The atomiser spacing is measured in metres, and recorded. Hence the intended volume of application is calculated using Equation (10.2), given previously.

Selecting rotational speed and metering orifice

By reference to the machine's handbook the correct rotational speed and size metering orifice are selected which will provide the calculated nozzle output and the drop size required. The pressure is set to the recommended level.

Checking atomisers

The orifice plates are fitted and the spray patterns are checked visually. Any rogue atomiser heads are stripped down and serviced. The outputs of all the individual heads are compared by use of a measuring cylinder. Outputs should not vary between heads by more than ± 5%.

Calibration

Calibrating the sprayer

Using a calibrated vessel, the output from four atomisers, at least one from each boom section, is measured and compared with the calculated atomizer output. If the output differs from the calculated output, the pressure should be altered and the calibration repeated.

Field-use calibration

Because the products applied through rotary atomisers are very concentrated, the output from one head must be checked with spray mixture when the first tank-load is mixed up. If the output varies from the calculated output, the pressure should be altered and the calibration respected. The following information should be recorded for future use: the orifice size fitted; the application volume; the spray pressure; the drop size; the rotational speed of heads (rev/min); the tractor gear; the tractor speed; the tractor rev/min; and the tractor wheel size.

Granule applicators

There are two main types of granule applicators. Some are designed specifically for the application of pesticide granules, and others are combined fertiliser/pesticide granule spreaders. Before commencing the application of a herbicide with either type of granule applicator, it is important that:

- The machine is correctly assembled
- The spreader is fitted with the correct metering rollers for the type of product to be applied
- All parts must be in good working order – the booms horizontal, the tubing free from obstruction, the spreader plates entire and in their original shape, and the metering rollers functioning correctly without excessive wear
- All parts must be dry
- All parts requiring lubrication must be lubricated carefully, with no oil or grease getting into contact with the granules

Calibration

Unlike aqueous sprays, the different sizes and densities of herbicide granules mean that granule spreaders must all be calibrated with the herbicide to be used. For many types of pesticide and spreader, the manufacturers have collaborated and suggest settings for calibration. These settings are only suggestions, however, and because of variations between individual machines and other factors such as wear of the metering device a calibration check is still essential. The method for checking a granule spreader is essentially the same as for a field crop sprayer, and for that matter any other application device. Equation (10.3) is used.

$$\begin{matrix}\text{flow rate}\\ \text{(kg/min)}\end{matrix} = \frac{\begin{matrix}\text{dose}\\ \text{(kg/ha)}\end{matrix} \times \begin{matrix}\text{speed}\\ \text{(km/h)}\end{matrix} \times \begin{matrix}\text{swath width}\\ \text{(m)}\end{matrix}}{600} \tag{10.3}$$

With the granule spreader set up according to the manufacturer's recommendation and half-filled with product, the true forward speed is ascertained by timing the spreader over a distance of 100 m in the field at the intended spraying speed. Then Equation (10.4) applies.

$$\begin{matrix}\text{speed}\\ \text{(km/h)}\end{matrix} = \frac{360}{\text{Time to travel 100 m (s)}} \tag{10.4}$$

The tractor speed and rev/min are recorded, and the metering mechanism is set to the manufacturer's recommendations appropriate to the product, speed, and p.t.o. r.p.m. Most granule spreaders have two sets of metering rollers, each of which feeds product to half of the machine. One roller is isolated and the other has a collecting tray placed beneath it, to collect the output of half the swath width of the machine. The fan must be either disconnected or blanked-off for calibration. The machine is set in operation for a minute or more until the operator is sure that the metering mechanism is fully primed. The granules collected in the tray during the priming period are returned to the hopper. The calibration is now checked by setting the tractor r.p.m. to that at which the speed test was carried out, then the output of the granule spreader is collected and weighted over 1 minute.

For example, if the product had an application rate of 25 kg/ha and was to be applied through a 12 m spreader, a typical calibration might be as follows.

time taken to travel 100 m in 5th gear at p.t.o speed $= 50\,\text{s}$

Then

$$\text{forward speed} = \frac{360}{50} = 7.2\,\text{km/h}$$

$$\text{output required from half the width of the 12 m spreader} = \frac{25 \times 6 \times 7.2}{600} = 1.8\,\text{kg/min}$$

The quantity of chemical delivered over the period of 1 minute is collected and weighed, and if it is incorrect the machine is adjusted accordingly.

Maintenance and cleaning

After use, the granule spreader must be cleaned down as carefully as a sprayer. All unused granules and dust must be removed, as any accumulation of herbicide is a potential hazard when the machine is next used. Heavy deposits of dust and debris will also affect the flow of subsequent products through the machine. The granules themselves must be stored in a cool, dry environment. Damp granules flow erratically and cannot be applied accurately.

Band sprayers

The purpose of band spraying a row crop is primarily to economise in the amount of expensive herbicide used. In addition, on certain soil types liable to ‘blow’ it is possibly an advantage to retain some weed cover between the rows until such time as the crop is big enough to give some protection to the soil. At this stage the weed cover can easily, and safely, be removed by a tractor hoe. Band spraying is also considered a good practice in that it reduces to a minimum the amount of chemical put on the soil.

Pre-emergence band spraying is normally a simple operation in that each nozzle is attached to the rear of a seeder, and if properly adjusted places a band of spray immediately over the line of seeds. The main problem is that the low tractor speeds required for satisfactory sowing necessitate the use of nozzles having correspondingly low outputs. Where wettable powders are used this can lead to an annoying frequency of nozzle filter blockage. If coarser filters are substituted this may lead to undue nozzle tip blockages. On a very long field it may be necessary to top-up the seeders at the end of every row. Similarly it may be necessary to top-up the band sprayer tank at the same time, and before it has emptied. If at this stage the tank is one-quarter full then the full amount of chemical for a tankful must not be added to the tank before re-filling with water, otherwise overdosing will occur – only three-quarters of the normal amount should be added. An alternative is to keep a quantity of the chemical mixed at the correct strength in a tank on the headland, topping-up the sprayer from this. With this system the tank must be kept agitated to ensure that the correct proportion of chemical to water is maintained for each topping-up.

Post-emergence band spraying is a more skilled operation. The band sprayer must be matched with the original drilling. If the seed was sown in, say, five rows at a time, then the band sprayer must have five nozzles or a multiple of this figure. Moreover, the sprayer tractor must follow in the wheelings of the seeding tractor in order to ensure continual matching of the nozzles with the rows. Although the original wheelings may be visible from the headland, it is often impracticable to drive accurately along them when there is a heavy cover of weeds. It is essential to keep an eye on the lines of crop and drive accurately so that a nozzle is directly over each row all the time. Obviously a rear-mounted band sprayer makes this almost impossible to achieve. A front-mounted sprayer permits the driver to look straight along one row and keep the appropriate nozzle over that row. A pressure gauge should be mounted as close as possible to that nozzle so that the driver never needs to take his eye off the row he is following. Post-emergence band sprayers should *not* be mounted under the tractor, behind the front wheels. This is because the air from the tractor cooling fan is liable to disturb the spray pattern on the rows under the tractor.

Band sprayer nozzles

Several types of nozzles are available for band spraying. Nozzles giving an even dose across the band are flat fan nozzle tips very similar in appearance to those used for overall spraying. However, they must not be used for overall spraying as their spray pattern will give rise to severe striping. Generally these tips, although giving an even volume of spray across the band, produce a relatively coarse spray at the edges of the band. This is quite satisfactory for pre-emergence spraying – the coarser spray is liable to be reflected off a number of weed species. Where this happens poor control of difficult weeds can be seen at the edges of the band, making accurate hoeing later on much more difficult.

Conventional flat fan nozzles give a reduced dose at the edges of the band. Where a herbicide is in use which has a high margin of safety for the crop, this type of tip is favoured because it ensures adequate weed control in the crop row, where no hoeing can be carried out except by hand or using complex hoeing devices.

Nozzles which give a higher dose at the edges of the band, e.g. hollow cone spray nozzles, are recommended where there is some risk to the crop of damage or delayed growth when overdosing occurs. The slight overdosing at the edges of the band makes for easier tractor hoeing later on, at the same time ensuring slight underdosing on the crop line. In addition, when the light falls on the crop from certain angles the spray from hollow cone nozzles is often easier to see from the driver's cab, than that from a flat fan.

Nozzle output

Each nozzle must pass precisely the correct volume of liquid to ensure that some rows are not overdosed at the expense of others. Further, each nozzle must produce a good spray distribution across the band. A heavy streak or a light streak in the pattern close to or over the crop line could give rise to crop damage or make hoeing difficult, respectively. If any tips are worn or damaged they must be replaced by a complete matched set of nozzles. It is not advisable to replace one nozzle by a new one which is not matched to the relatively worn remainder. Nozzle outputs can be tested with the sprayer stationary, and this should be done before taking the sprayer out to the field. Band sprayer manufacturers normally can provide ready-matched sets of tips. A sprayer built on the farm should be designed to operate with readily available matched sets of nozzles.

Band width

It is essential to maintain a constant correct band width. If the nozzles are mounted on a rigid bar, the slightest undulation of the ground will cause variation in band width and hence variation in dose. When spraying post-emergence, each nozzle should be mounted on its own wheel, to maintain it at a constant height above the soil (performing a function similar to that of a seeder unit, but with the wheel running alongside the row of plants). As the wheel (or the seeder unit) will tend to sink into the soil a little, thereby narrowing the band width, it is always essential to check the band width in the field under the normal soil conditions. Cone nozzles will have to be raised to increase the width of band, and vice versa. The same technique can be used for flat fan nozzles, or alternatively these can be angled to the direction of the row to reduce the band width.

Calibration

This is essentially the same as for the hydraulic ground-crop sprayer. First, the label on the chemical pack must be checked for recommended volume of application, spray quality, band width and nozzle type. A trial run should be carried out in the field to establish the optimum operating speed, and a gear which gives a p.t.o. speed of about 540 rev/min. From a speed check over 100 m, using gear and rev/min as above, the time taken, in seconds, to cover this distance is measured and the forward speed is established from Equation (10.1) given previously. The band width (in metres) required for the product is recorded. The output per nozzle required to achieve the intended volume of application is established, using Equation (10.5), and recorded.

$$\underset{\text{(l/min)}}{\text{nozzle output}} = \underset{\text{(km/h)}}{\text{speed}} \times \underset{\text{(m)}}{\text{band width}} \times \underset{\text{(l/ha)}}{\text{volume of application}} \div 600 \tag{10.5}$$

By reference to the nozzle manufacturer's data charts or cards, or to ADAS Advisory Lists, the type and size of nozzle are selected which will provide the calculated nozzle output and the spray quality required. The pressure is set to the recommended level. The nozzles are fitted and the spray patterns and alignment are checked visually. Any rogue nozzles are replaced. The output of individual nozzles is compared by use of a nozzle flow meter (e.g. Jetchek) or a recording jar. Nozzles with more than 5% variation from the average should be replaced.

A calibrated vessel is used to measure the output from four nozzles, at least one from each boom section. This output is compared with the calculated nozzle output. If the output of these four nozzles differs by only a small amount from the calculated output, the pressure should be altered and the calibration repeated. However, if the output differs by a large amount, calibration and calculations need to be re-checked and the size of the nozzle should be changed if necessary.

The correct band width is obtained by spraying water and at least 0.1% wetter over dry concrete or dry soil, and adjusting the height of the nozzles until the correct band width is obtained. The nozzle tips fitted, the application volume, the band width, the nozzle height, the spray pressure, the spray quality, the tractor gear, the tractor speed, the tractor rev/min and the tractor wheel size should all be recorded for future use.

Band area

For the purposes of purchasing sufficient chemical for a band spraying operation it is necessary to calculate the band area to be sprayed (Equation (10.6)).

$$\underset{\text{(ha)}}{\text{band area}} = \underset{\text{(ha)}}{\text{field area}} \times \underset{\text{(m)}}{\text{band width}} \div \underset{\text{(m)}}{\text{row width}} \tag{10.6}$$

For example, a 15 ha field cropped with 0.5 m row spacing using a band width of 0.18 m requires sufficient chemical to spray $(15 \times 0.18)/0.5 = 5.4$ h of band.

Knapsack sprayers

The method is fundamentally the same as for a ground-crop sprayer except that knapsack sprayers are generally less sophisticated and have few options for adjusting spray pressure. Some knapsacks are fitted with either a pressure regulator or a gauge, and rely on the skill and consistency of the operator for a uniform application.

Calibration of a single land nozzle

First the herbicide label and sprayer handbook should be read. These will provide the correct range of spray volumes for applying the herbicide and may advise a particular type and size of nozzle, or spray quality. The forward speed should be checked. The knapsack sprayer is half-filled with water, then the operator sprays over a measured distance of 100 m at normal walking speed in the field, and records the time taken to cover this distance. This exercise should be repeated at least three times, and the average time (in seconds) taken used to calculate the spraying speed (km/h) as equal to 360/time. By referring to nozzle charts, a nozzle is selected which should produce a suitable application rate consistent with constraints of spray quality, operating pressure and swath width. The nozzle is fitted to the sprayer and the sprayer is half-filled with water + 0.1% wetter, and sprayed over dry concrete. The swath width (m) of wet mark on the concrete is recorded, and can be adjusted by raising or lowering the nozzle height as necessary. The flow rate (l/min) through the nozzle is checked by collecting the output from one minute's spraying, recording the pressure setting where appropriate. The volume of application is calculated from Equation (10.7).

$$\begin{matrix}\text{volume}\\ \text{(l/ha)}\end{matrix} = \frac{\text{flow rate (l/min)} \times 600}{\text{swath width (m)} \times \text{speed (km/h)}} \tag{10.7}$$

Should the volume of application be outside the range recommended on the herbicide label, it should be altered by fitting a different-sized nozzle for a large deviation, or altering the pressure for a small deviation. When spraying, the spray volume, the forward speed, the nozzle type, the nozzle height, the spray quality and the swath width should be recorded.

Say, for example, that the herbicide label requires an application rate of 200–400 l/ha, the nozzle fitted to the sprayer produces an output of 2.2 l/min at 1.5 bar pressure, the swath width is measured as 1.2 m and the forward speed is 3.6 km/ha. Then spray volume is (2.2 × 600)/(1.2 × 3.6) = 306 l/ha.

Sprayer faults

Much can go wrong with the spray operation. Nevertheless, modern sprayers are the result of many years of evolution and are built to be robust. Table 10.2 is a diagnostic chart for sprayer faults.

Errors in applying herbicides

Efficient selective weed control depends amongst other things upon applying the correct dose of a herbicide uniformly to the target across the whole of the area to

Table 10.2 Fault-finding and correction chart for sprayers

Fault	Probable cause	Remedy
Fails to spray when turned on	Nozzles assembled incorrectly	Re-assemble correctly – see manufacturer's handbook
	Outlet at bottom of tank blocked	Disconnect outlet pipe and clear
	Filter on suction side of pump completely blocked	Dismantle, clean and re-assemble
Sprays for a short time only after switching on	Air inlet to tank blocked.	Clean vent hole, otherwise the tank may collapse
	Filter on suction side of pump blocked rapidly	Dismantle, clean and re-assemble – determine and remove cause of blockage
Spray is not even across the spray bar	Some nozzle filters or tips are becoming blocked	Remove, clean and refit correctly
	Nozzle tips are not all the same size	Check the number on each tip and change any wrong tips
	Nozzle tips may be worn; check output	Replace worn tips with new ones; calibrate
	Nozzles at each end of the spray bar have a lower output	Check pressure at end of bar by replacing end nozzle with pressure gauge; if pressure is lower at the end of the bar, the nozzle output is too large for the pump's capacity; fit smaller tips or change pump, if worn
Pressure gauge reading going up; spray volume from nozzles decreasing	Nozzle filters blocking up gradually	Dismantle, clean and refit; check pressure has returned to normal
	If cleaning nozzle filters has no effect, gauge may be strained	Check that gauge returns to zero when the spray is turned off; if not, replace with a new gauge
Pressure gauge reading declining	Main filter on suction side of pump blocking up	Dismantle, clean filter and replace
	If filter cleaning gives no improvement, nozzle tips may be worn	Replace tips with new ones of the same size and make
	If replacing nozzles gives no improvement, pump may be worn	Replace with new or reconditioned pump
	Airlock in the pump	Take tension off the relief valve spring and operate the pump to allow air to escape through the agitator tube

Contd.

Table 10.2 *Contd.*

Fault	Probable cause	Remedy
Spray fans or cones very narrow	Pressure too low	Check that pressure and output are within the range recommended for the sprayer; use smaller tips if necessary
	Pressure too low and air spluttering out of nozzles	Check that the tank is not very nearly empty; if not, there may be an air leak between the tank and the pump, or in the pump itself; locate and repair the leak
Coarse foam in the spray tank, on top of the liquid	Faulty agitation	If mechanical agitation is used this is too violent and is beating air into the liquid; if there is a return pipe above the level of the tank liquid, extend it to the bottom of the tank or deflect output against the tank more carefully
Very fine foam in the liquid in the tank	Air leak in the system, probably between the tank and the pump or in the pump itself	Locate and repair leak
Spray fans or cones streaky when viewed against a dark background	Nozzle partly blocked by minute hairs or flakes	Remove tips and clean; refit correctly and test
	Nozzle clean but still streaky – probably faulty or worn tip	Replace tip with a new one of the same size and make; test
Excessive pulsation of the spray pattern	Damaged pump inlet valve	Strip and repair pump
	Incorrect air pressure in the equalising chamber	Set pressure to 2 bar and adjust in small increments if necessary
Output of pump below expectation	Damaged exhaust valve	Strip pump and replace
Spray pressure drops as tank empties	Air entering tank outlet to the pump	Fit anti-vortex plates, redirect jet agitator or reduce pump speed

be sprayed, while minimising off-target losses. Some common errors and possible remedies are given in Table 10.3.

Incorrect doses

Underdosing presents only the problem of unsatisfactory weed control, which can sometimes be rectified by further efforts by the grower.

Overdosing is more serious; it is a criminal offence. It may also damage the crop and leave residues that are harmful to the following crop and the consumer.

Table 10.3 Common errors which occur in spraying and their possible remedies

Observed error	Probable cause	Remedy
Longitudinal stripes	Nozzles too low	Adjust nozzle height
	Pressure too low	Adjust pressure or remove blockage
	Worn or damaged nozzles	Replace nozzles
	Foam in spray liquid	Find cause of foaming
Short intermittent stripes	Spray boom roll or bounce	Reduce speed; check linkages for free movement
Intermittent stripes at boom end	Spray boom yaw	Reduce speed; check linkages for free movement
Uneven patchy results	Too fine a spray quality	Fit coarser-quality nozzles
	Excessive wind at application	Don't spray

Overdosing can be caused by spillage: all herbicides should be handled carefully. Spraying from a stationary sprayer, which often occurs when the sprayline is purged on the headland before starting off across the field with a fresh tank load, results in very heavy herbicide loads on the crop and soil. It can be minimised if the operator records the time taken to purge the line, and uses this information in practice. Dribbles from nozzles cause localised overdosing, as do leaking joints and components on the sprayer and pipework that foul the spray pattern. These are all items of maintenance. Overdosing will occur if the tractor slows down when travelling uphill or suffers wheel slip, unless there is an electrical or mechanical system fitted to compensate. Overlapping of the spray swaths is a common cause of overdosing; accurate bout matching and switching off the sprayer at the headland are essential. Failure to observe herbicide mixing instructions are a frequent cause of heavy overdosing at the start of spraying a new load, and reduced weed control for the remainder. Mistakes in calculation or calibration will inevitably lead to the wrong dose being applied.

Herbicide drift

Drift must be minimised at all times. It is potentially damaging to neighbouring crops and hedgerow flora and fauna, and creates an impression of irresponsibility to the casual observer, even in low-risk situations. Drift may occur in three ways. Spray drift is the result of the smaller drops in the spray being carried off-target by wind or convection currents. Vapour drift occurs when the vapour from a volatile herbicide is carried away from the target area during or after spraying. It is most likely to occur in warm, still weather. A gentle breeze will tend to disperse the vapour to such an extent that there will be no hazard. 'Blow' is the movement by high wind of dried spray particles or of soil impregnated with the herbicide

Table 10.4 Wind speed and when to spray

Approx. airspeed at boom height (km/h)	(mph)	Force on Beaufort scale (at height of 10 m)	Description	Visible signs	Spraying
< 2	< 1.2	0	Calm	Smoke rises vertically	Avoid spraying
2–3.2	1.2–2	1	Light air	Direction shown by smoke drift	Avoid spraying
3.2–6.5	2–4	2	Light breeze	Leaves rustle, wind felt on face	Ideal for spraying
6.5–9.6	4–6	3	Gentle breeze	Leaves and twigs in constant motion	Avoid spraying herbicides
9.6–14.5	6–9	4	Moderate	Small branches moved, raises dust or loose paper	Spraying inadvisable

away from the area originally treated. There is guidance on when not to spray in relation to windspeed (Table 10.4)

Spray drift

This is the most common form of herbicide drift. Growth regulator herbicides are the most dangerous from this point of view because quite small amounts which can travel considerable distances may be highly damaging. Contact herbicides are generally less damaging but will cause necrotic spotting on susceptible crops. Soil-applied herbicides which have no foliar activity have little risk of causing damage over a distance of more than a few metres. The amount of herbicide carried away is likely to be too small to have any effect when it is deposited on the soil again.

Spray drift can be reduced or prevented by one or more methods.

Spraying should be done only when there is a gentle breeze blowing away from a susceptible crop. One should avoid spraying in strong winds, or in warm, still conditions (particularly evenings) when convection currents rise from fields and fine spray drops take a long time to settle.

Choice of nozzle is critical. Air induction nozzles are probably the most effective of all the nozzle types for reducing spray drift.

The spraying of herbicides next to susceptible crops should, if possible, be carried out before these crops appear above the soil.

Use of fine sprays should be avoided; the coarsest-quality spray recommended on the label should be used. Operators of machines fitted with electrical or mechanical constant-volume devices must pay particular attention to their forward speed. A doubling of the forward speed results in a corresponding four-fold increase in spraying pressure, which greatly increases the potential for drift. Conversely, such devices can beneficially be used to reduce the potential for drift by reducing the forward speed of the machine.

The nozzles should be kept as close as possible to the soil, weeds or crop, whichever is the tallest, at a level consistent with the minimum recommended nozzle height.

Where a susceptible crop is above the ground and is on the downwind side of a crop requiring treatment, the operator should leave an untreated strip of sufficient width along the edge. The untreated strip may be sprayed later when the wind is blowing away from the susceptible crop.

Vapour drift

Vapour drift is generally associated with the ester formulations of certain growth regulator herbicides. It is best avoided by choosing alternative products for high-risk situations.

Blow

Damage by blow was mainly associated with the now-obsolete active ingredients DNOC and Dinoseb. Where there is a risk of blow onto a susceptible crop, the operator must either spray before that crop has emerged, or leave a suitable width of untreated ground beside it.

Decontamination of sprayers and disposal of waste material

The question of disposal should be considered before herbicides are purchased. Quantities and pack sizes should be appropriate to the task in hand and the shelf-life of the product. It is preferable, wherever possible, to choose products and quantities that will not cause disposal problems.

Managing waste

The point where a load runs out should be marked. Spray should not be wasted by over-spraying an already-treated area because the maximum permitted dose and/or number of applications may then also be exceeded. Nor does one want unsprayed areas, which can become weed- or disease-infested. One can identify the point where spray runs out by setting the position on the in-cab spray monitor or with a cane or other marker. If a marker is used, it should be positioned alongside the front wheel and care should be taken not to walk in the sprayed crop.

The last sprayed load should be managed so that it allows tank-rinsing water to be sprayed out. If the spray is being applied at full rate, it should also be ensured that at least a 10% dose reduction is applied to an area where the tank rinsings can be sprayed out. This is often the last headland, but if a high level of control is wanted there, another area can be reserved.

Tank rinsing is always best carried out in the field. Sprayers with clean rinse-water tanks and internal tank-rinse nozzles make this easy. Tank-cleaning additives help with this and are essential when using products based on sulphonyl urea. In all cases triple rinsing and a standing recirculation period should be used before the washings are sprayed out. If rinse tanks are not fitted they can often be retrofitted at reasonable cost, sometimes as a front-mounted tank. Otherwise a small towed bowser of water taken out with the last load solves a disposal problem back at the yard.

The cleaning of booms, nozzles and filters is very important. Triple rinsing does much to clean out the nozzle bodies, boom and line filters but they should all be thoroughly cleaned when changing products, especially when moving on to a sensitive crop.

Washing the outside of the sprayer can create point-source pollution of water if it is not done carefully. A washdown area can be on an Environment Agency-approved piece of waste land which is appropriately fenced and signed. If the farm has a concrete yard great care is needed, especially if the yard drain has a sensitive outfall. However, suitable catch tanks, with diverters to send rainwater to a soakaway when the pad is not in use, are a solution. Contaminated water can then be safely collected by an authorised waste disposal company, or cleaned up on the farm using a specially designed filtration unit. Alternatively, the sprayer needs to be washed off in the field, away from any water contamination risk. This spreads the chemical loading at normal field rates and, to make it simpler, many of the new sprayers have hose reels and washdown brushes as standard fittings. Another solution comes from Sweden – the Biobed. This is a lined pit with a high-humus filling and two wheeling tracks for the sprayer unit. Washing down is carried out over the bed and bioactivity in the humus inactivates and makes safe the pesticide residues.

Disposal of empty containers

After the contents of a container have been added to the spray tank, the container should be rinsed out and the rinsate added to the spray tank. The empty container must be stored in a secure used-container compound, until it is disposed of. Where possible, the need for disposal may be avoided by using returnable refillable containers such as the LinkPak. Well rinsed plastic containers may be buried or burnt according to the practices advised in the Green Code. Where incineration is the preferred option, the best practice is to use a BAA-designed farm incinerator (Fig. 10.1). The advantage of this incinerator is that the internal temperature reaches 800°C, producing negligible smoke and effectively destroying any residual chemical. Burning on an open fire is less hot, and may result in incomplete combustion.

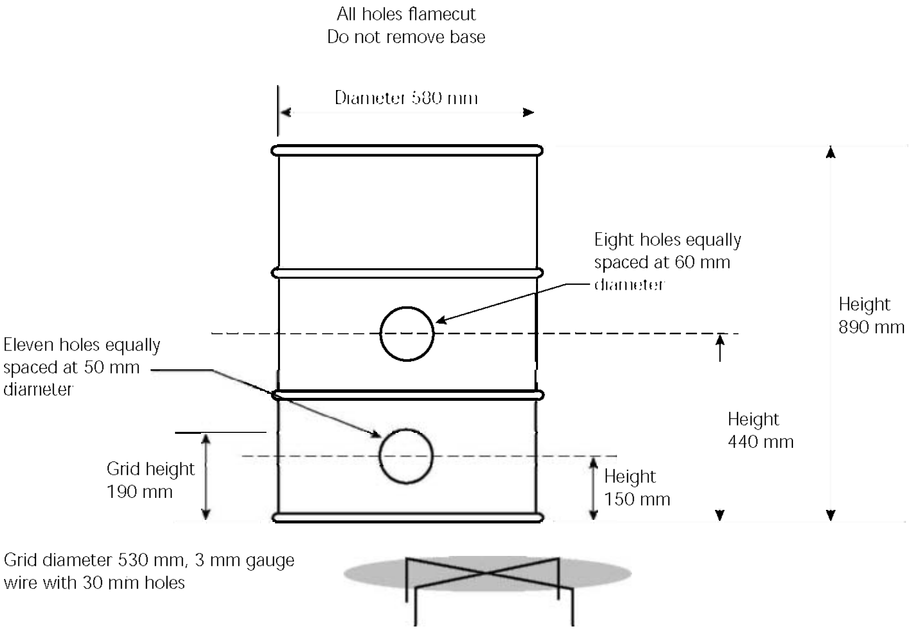
All holes flamecut
Do not remove base

Fig. 10.1 Design of BAA incinerator.

Metal containers should be rinsed, punctured, flattened and disposed of either by the local council or by burying to a depth of at least 0.8 m in a site that is on land occupied by the person disposing of the container and that is without risk of pollution to surface or ground-water sources. The area should be marked and a record kept of the site and the materials buried.

Storage of herbicides

The farm herbicide store should have particular important characteristics. It should: be secure against thieves and vandals, with locked doors and bolted windows; be dry, well ventilated and protected from frost; be sited well away from public roads, private houses, livestock buildings, as well as stores for fodder, fertiliser, fuel or any combustible materials; and be sited to prevent any pollution hazard to watercourses, ponds, ditches, surface catchment areas and bore-holes. The store should also have floors and walls which contain spillage or flooding at a level below the stored containers and also prevent spilt liquids from seeping into the ground, and ideally it should have separate washroom with hot and cold running water. Soiled protective clothing should be stored separately from clean protective clothing and laundered as soon as possible. As part of the farm emergency plan there should be easy access for the fire service and any other emergency vehicles and a stock list of all stored pesticides, with separate copies in the farm office and on display in the washroom. One copy of the list should be readily available to the fire service. The store should have a warning sign in a prominent position outside the store at 2 m above the ground, and have adequate First Aid facilities.

Where less than 50 litres of liquids or 50 kg of powders and/or granules are to be stored, a ventilated and lockable steel cabinet would be adequate. As a general rule, one can expect a shelf-life of at least two or three years if chemicals are correctly stored. Shelf-life will largely depend on the stability of the active ingredient and its formulation, and can in some temperatures be much greater than three years. Chemicals should be date-marked as they are put into store, and new bottles should be placed at the back of the shelves, to ensure that the old containers get used up first.

References and further reading

Nozzle Selection Handbook BCPC: Farnham.

Chapter 11
Herbicide-Resistant Weeds

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Introduction

The evolution of weed populations resistant to herbicides is an increasing problem in many countries. The aim of this chapter is to explain what is meant by resistance, the extent of the problem, how it develops, the mechanisms responsible and how to prevent and manage resistant populations.

Definitions

Herbicide resistance can be defined as 'the *inherited* ability of a weed to survive a rate of herbicide which would normally result in effective control'. A key aspect is that resistance, in this context, is an *evolutionary* process, whereby a population changes from being susceptible to being resistant. Individual plants do not change from being susceptible to being resistant; rather, the *proportion* of resistant individuals within the population increases over time.

Confusion can result from the use of the term 'resistant' (R) when assigned to weeds for their response to individual herbicides, on pesticide product labels for example. In that context, resistance refers to the *innate* response of those weeds to a specific herbicide rather than a *change* due to selection. For example, *Galium aparine* (cleavers) is referred to as being resistant to MCPA, but that weed has always been insensitive – there has been no change in response. Thus this chapter deals with resistance that has *evolved* in individual species due to selection imposed by herbicides.

There has also been confusion over the terms 'resistance' and 'tolerance'. They are used inconsistently and often interchangeably. The use of the term 'tolerance' is being discouraged, in favour of qualifying the description of resistance, e.g. 'partial resistance'. Generally, resistance to doses of herbicides which are normally effective in the field is not widespread in a weed population before the selection imposed by use of herbicides.

The term 'cross-resistance' is often used to describe cases in which a weed population is resistant to two or more herbicides (of the same chemical class, or different ones) due to the presence of a single resistance mechanism. The term 'multiple resistance' is often used to refer to cases where resistant plants possess two or more distinct resistance mechanisms. However, it is becoming increasingly difficult to define what is a single, distinct mechanism. Consequently the term 'multiple herbicide resistance' is often used to indicate resistance to a range of herbicides with different modes of action, regardless of the mechanisms involved.

It should be recognised that no universally accepted definitions of 'resistance', 'cross-resistance' or 'multiple resistance' exist, and other interpretations will often be encountered.

The incidence of resistant weeds

The number of cases of resistance to insecticides and fungicides increased rapidly after 1950 and 1960 respectively. In contrast, the recognition of herbicide resistance as a serious problem is more recent, despite the widespread use of selective herbicides for 50 years. MCPA and 2,4-D were first used in the late 1940s, and there were a few reports of partial resistance to these herbicides during the 1950s. However, since the detection of simazine-resistant *Senecio vulgaris* (groundsel) in 1968, there has been a steady increase in the number of resistant species. Figure 11.1 shows the increase in the number of new resistant biotypes recorded worldwide – approximately nine new resistant biotypes per year since 1980.

By July 2001, 249 herbicide-resistant weed biotypes in 52 countries had been recorded on the international herbicide-resistance data base, which is funded by the Herbicide Resistance Action Committee (HRAC) and maintained by Ian Heap (www.weedscience.com). The term 'biotype' is used as some weed species have developed resistance to more than one class of herbicide, so the same species

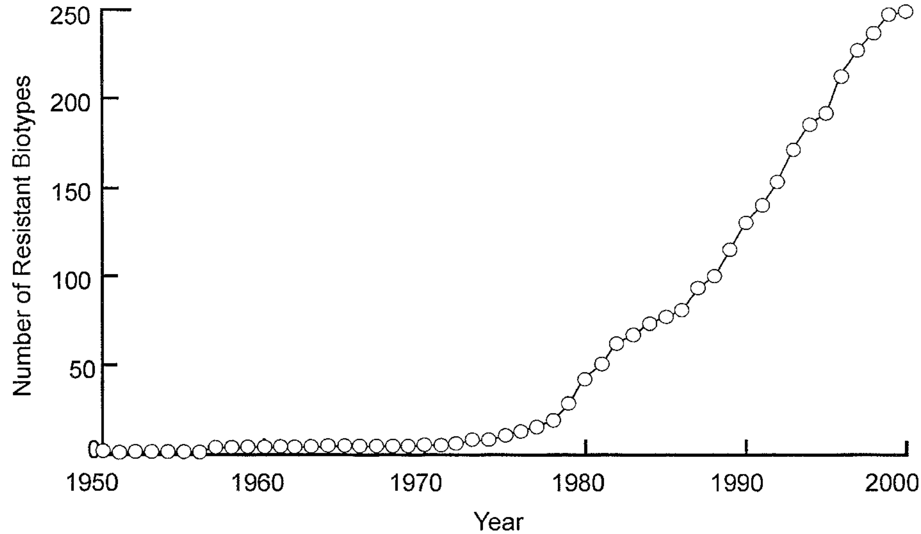

Fig. 11.1 The chronological increase in unique cases of herbicide-resistant weeds worldwide (Heap, 2001).

may occur more than once in the data base. The total of 249 resistant biotypes represents 153 distinct species, of which 91 are dicotyledonous and 62 monocotyledonous.

There are no clear relationships between plant families or genera and their tendency to evolve resistance, although grass-weeds tend to be over-represented in the list of resistant biotypes (Table 11.1). Resistance has usually developed in one, or at most a few, species in a weed community, despite all being exposed to the same intensity of herbicide use. Whilst grass weeds account for 33% of all resistant species and 40% of all resistant biotypes, they account for only 25% of the world's major weeds. Other families which have a disproportionately high number of herbicide-resistant species, compared with their representation as principal weeds, are Amaranthaceae, Brassicaceae, Chenopodiaceae and Scrophulariaceae.

Table 11.1 The number and percentage of resistant species by family, and the percentage of species considered principal weeds by Holm *et al.* (1991, 1997) for each of these families (from Heap, 1999)

Family	Number of resistant species in family	Resistant species (% of total)	Weed species (% of world's principal weeds)*
Poaceae (Gramineae)	48	33	25
Asteraceae	29	20	16
Amaranthaceae	9	6	3
Brassicaceae	9	6	4
Chenopodiaceae	7	5	2
Polygonaceae	6	4	5
Scrophulariaceae	6	4	1
Alismataceae	3	2	1
Cyperaceae	3	2	5
Solanaceae	3	2	2
19 other families pooled	24	16	16
Total	147	100	80†

* The number of species within a family, as a percentage of the total, reported by Holm *et al.* (1991, 1997) as being principal weeds of the world.

† An additional 20% of the species listed by Holm *et al.* (1991, 1997) were in families where no other species has evolved herbicide resistance.

The 52 countries in which resistant weeds have been recorded are: USA (46 states); Canada (most provinces); 21 European; 9 South and Central American; 12 Asian; 5 African and 3 Australasian countries. The countries with the greatest number of different resistant biotypes are: USA (85 resistant biotypes); Australia (36); Canada (35); France (30); Spain (24); United Kingdom (22); Belgium (18); Israel (18); Germany (17). Ten years ago resistance was largely confined to temperate countries with intensive agricultural systems, especially in North America, Europe and Australia. Now the incidence of resistance is increasing in

Asian and South and Central American countries as these regions adopt more intensive agricultural systems and greater use of herbicides. This trend is likely to continue and is of concern because the range of herbicides available in many developing countries is often limited, with few alternatives available to the herbicides to which resistance develops.

Herbicide groups affected by resistance

Resistance to 15 different herbicide groups has been reported (Table 11.2). These groupings are those defined by the HRAC (Schmidt, 1997). The number of resistant biotypes that have evolved resistance to seven of the major herbicide groups world-wide is shown in Figure 11.2. This shows clearly that between 1980 and 1990 the majority of cases of resistance involved the triazine herbicides (e.g. atrazine and simazine). However, since 1990 resistance to other herbicide groups, especially the acetolactate synthase (ALS) inhibitors (e.g. sulfonylureas) and acetyl-coenzyme A carboxylase (ACCase) inhibitors (aryloxyphenoxypropionates = AOPP, 'fops,' and cyclohexanediones = CHD, 'dims'), has increased sharply. In 2000 the number of biotypes resistant to ALS-inhibiting herbicides exceeded the number resistant to triazine herbicides for the first time.

Whilst the number of biotypes that have evolved resistance continues to increase, it is important to recognize that this is only one way of measuring the global impact of resistance. The increase is almost certainly due, in part, to greater awareness of resistance, so more people are looking out for, and recording, resistance. Many resistant biotypes are very localised in distribution and have limited economic impact. Other resistant biotypes may be controlled simply by using herbicides with alternative modes of action. For example, weeds resistant to triazine herbicides have been controlled with reasonable success in many countries, usually by the use of alternative herbicides. The extent of the area affected by herbicide-resistant weeds, and the economic impact, are poorly documented in most countries because of lack of comprehensive survey data.

However, the evolution of resistance in situations where alternative herbicides are unavailable or ineffective, and in particular biotypes with multiple resistance to different groups of herbicides, poses a considerable threat. Some of the newer herbicide groups, which tend to be active at specific target sites, seem to be more vulnerable to resistance than older groups, so it should not be assumed that new herbicide developments will provide an easy answer. For example, despite the widespread use of synthetic auxin herbicides (e.g. MCPA, 2,4-D) since the early 1950s, relatively few weeds have evolved resistance. In contrast, acetolactate synthase (ALS) and ACCase inhibitors, which have been used extensively only since the early 1980s, have been implicated in a far larger number of cases of resistance.

Table 11.2 The occurrence of weed biotypes resistant to different herbicide groups by 2001 (Heap, 1999, 2001)

Herbicide group	Mode of action	HRAC* code	Example	Total number of resistant biotypes
ALS inhibitors	Inhibition of acetolactate synthase (ALS)	B	chlorsulfuron	69
Triazines	Inhibition of photosynthesis at photosystem II	C1	atrazine	63
ACCase inhibitors	Inhibition of acetyl-CoA carboxylase (ACCase)	A	diclofop-methyl	25
Bipyridyliums	Photosystem-I-electron diversion	D	paraquat	21
Ureas and amides	Inhibition of photosynthesis at photosystem II	C2	chlorotoluron	20
Synthetic auxins	Synthetic auxins (action like indole acetic acid)	O	2,4-D	20
Dinitroanilines and others	Microtubule assembly inhibition	K1	trifluralin	10
Thiocarbamates and others	Inhibition of lipid synthesis – not ACCase inhibition	N	tri-allate	6
Triazoles and others	Bleaching: inhibition of carotenoid biosynthesis (unknown target)	F3	amitrole	4
Glycines	Inhibition of EPSP synthase	G	glyphosate	3
Chloroacetamides and others	Inhibition of cell division	K3	butachlor	2
Nitriles and others	Inhibition of photosynthesis at photosystem II	C3	bromoxynil	1
Carotenoid biosynthesis inhibitors	Bleaching: inhibition of carotenoid biosynthesis at the phytoene desaturase (PDS) step	F1	flurtamone	1
Carbamates and others	Inhibition of mitosis/microtubule organisation	K2	propham	1
Organoarsenicals	Unknown	Z	MSMA	1
Arylaminopropionic acids	Unknown	Z	flamprop-methyl	1
Benzyl ethers	Unknown	Z	difenzoquat	1
Total number of unique herbicide-resistant biotypes				249

* Herbicide Resistance Action Committee (see Schmidt, 1997).

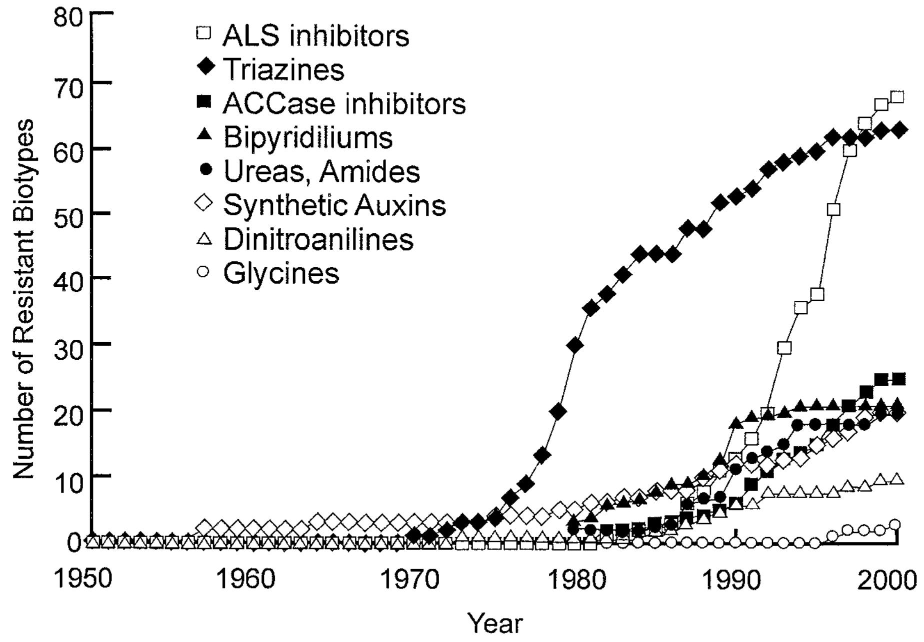

Fig. 11.2 The chronological increase in the number of herbicide-resistant weeds for eight herbicide groups (Heap, 2001).

Agronomic factors influencing the development of resistance

Most cases of resistance have occurred in situations where the same herbicides (or herbicides with the same mode of action) have been used repeatedly over a period of years, usually associated with intensive agricultural or horticultural systems involving crop monoculture (or at least very restricted crop rotations) and minimum tillage, systems in which herbicides have been relied upon to achieve high levels of weed control. Herbicide resistance has evolved within a range of crops, but the most widespread problems have occurred in maize, cereal and rice crops, or in horticultural situations such as orchards, nurseries and vineyards. Herbicide resistance has also evolved in non-cropping situations, such as roadsides and railways, following intensive use of herbicides such as atrazine.

It is important to recognise that there are several factors which limit resistance development. An appreciation of these factors can help in the development of management practices aimed at preventing and managing resistance. These factors are (1) the length of the weed life cycle, (2) the lack of mobility of weeds, (3) weed management by non-chemical means (e.g. cultivations, crop rotation) and (4) the seed bank in the soil.

In many cropping systems, especially in temperate climates, most annual weeds reproduce and produce seeds only once per year. In contrast, many insect and fungal pathogens are capable of producing several generations per year. On theoretical grounds, it would be predicted that the longer generation time for weeds would be a powerful factor slowing the rate of development of resistance. It may partly explain why herbicide resistance has developed later than insecticide and fungicide resistance, but it has not prevented resistance evolving within five years of the introduction of new herbicides such as the ALS and ACCase inhibitors. Consequently, the length of the weed life cycle does not seem to be as powerful a moderating influence as was once predicted.

In contrast to many insects and fungal spores which can travel long distances, most weeds are relatively immobile. Some weeds, e.g. *Kochia scoparia* (tumbleweed), are adapted for long-distance seed dispersal but propagules of many other weeds are likely to be moved only short distances, unless they are transported in contaminated crop seed, on harvesting and cultivation equipment or in straw. Transfer of resistant genes via pollen is possible in cross-pollinating species, but there is little evidence that this is an important means of gene transfer over long distances. Consequently, in comparison with insecticide and fungicide resistance, a farmer has greater control over the development and spread of herbicide resistance within the farm.

Herbicides are, of course, only one way of managing weeds. Cultural (non-herbicidal) management methods are widely practised; they are summarised in a later section of this chapter and in detail in Chapter 13. The seed bank in the soil will also provide a buffering effect on selection for resistance, especially in species with persistent seeds (Chapter 3).

Resistance mechanisms

Herbicide resistance can result from any inherited trait which allows plants to survive herbicide applications. This could be due to biochemical/physiological changes, morphological alterations which affect herbicide uptake or interception or phenological changes, such as changes in germination patterns. Most cases of herbicide resistance have resulted from alterations in site of action, metabolism or other biochemical functions, with very few reports of morphological or phenological changes having a major impact on herbicide activity. Although these general mechanisms of resistance are similar to some of the selectivity mechanisms in crops which enable them to survive exposure to herbicides, the specific mechanisms of herbicide resistance in weeds usually differ substantially from those responsible for crop selectivity.

Altered site of action (target site resistance)

This is the mechanism most commonly recognised as responsible for resistance. Most, but certainly not all, cases of resistance to triazine, ALS inhibitor, ACCase inhibitor and dinitroaniline herbicides involve inherited modifications to the site of action of the herbicide. Triazine herbicides are photosystem II inhibitors and in the majority of triazine-resistant weeds studied, resistance is due to a mutation in the *psb*A gene, which codes for the D1 protein. Molecular analysis has shown that resistance is due to the same mutation (Ser_{264} to Gly) in many different resistant species, although recently it has been shown that resistance can be conferred by other mutations. This mutation decreases binding of *s*-triazines (e.g. atrazine) in the thylakoid membrane of the chloroplast. Resistance is usually absolute, such that no herbicidal activity is evident on resistant plants, even at many times the recommended doses. Triazine-resistant weeds exhibit varying degrees of cross-resistance to other herbicides which inhibit photosystem II, such as triazinones and uracils. Although these herbicides bind to the same domain within photosystem II, each has a specific orientation in the binding niche; this probably explains the differences in cross-resistance patterns.

Resistance to ALS inhibitors, such as chlorsulfuron, is due to an alteration of the gene encoding for the ALS (acetolactate synthase) enzyme, which catalyses the first steps in the biosynthesis of the amino acids leucine, isoleucine and valine. This enzyme is the target for inhibition by five chemically different groups, including the sulfonylureas and imidazolinones and triazolopyrimidines. There are now more cases of resistance to ALS inhibitors than to any other chemical class. In contrast to triazine resistance, several different mutations have been identified conferring resistance to ALS inhibitors. However, such mutations result in differing degrees of resistance to the different groups of ALS inhibitors. Many amino acid substitutions at the Pro197 position have been found and these mutations confer high resistance to sulfonylureas, high/moderate resistance to triazolopyrimidines and low or no cross-resistance to imidazolinones. However, mutations at other sites confer different patterns of resistance. Consequently, it is difficult to predict to what extent resistance will affect different groups of ALS inhibitors. It is also possible for different mutations to occur within the same species at different locations, so the patterns of cross-resistance within the ALS inhibitor class may vary considerably at the whole-plant level. This will have important implications in the management of resistant populations.

There are two groups of ACCase-inhibiting herbicides, the cyclohexanediones (CHD) and the aryloxyphenoxypropionates (AOPP). Although chemically dissimilar, both groups act by inhibiting plastidic ACCase, which is involved in lipid biosynthesis. This plastidic ACCase is fundamentally different in monocotyledonous (sensitive) and dicotyledonous (insensitive) plants. Consequently ACCase-inhibiting herbicides (e.g. fluazifop-P-butyl, sethoxydim) are widely used to control grasses in broad-leaved crops. However, metabolism of ACCase inhibitors such as diclofop and tralkoxydim within some monocotyledonous crops (e.g. wheat) is the basis of selectivity allowing selective control of grass weeds in cereals. Resistance to ACCase inhibitors has arisen in many different grass-weeds due to an altered target site. In some cases there is resistance to both AOPP and CHD herbicides, whilst in other cases resistance is more specific, affecting only AOPP or CHD herbicides. This situation can exist within the same species. For example, *Avena fatua* (wild oat) resistant to AOPP but not to CHD herbicides occur in the UK, whereas some populations of the same species in North America are resistant to both groups. This suggests that several different mutations can occur, each conferring a different pattern of cross-resistance to different AOPP and CHD herbicides. Much less is known about the molecular basis of resistance to ACCase inhibitors than for triazines and ALS inhibitors. Recently, an ACCase mutation conferring herbicide resistance to the CHD herbicide sethoxydim in *Setaria viridis* was identified at the molecular level for the first time. Studies to identify other mutations in other species are currently in progress.

Resistance to dinitroaniline herbicides (e.g. trifluralin) and auxin-type herbicides (e.g. 2,4-D) is also associated, at least in some instances, with target site insensitivity.

Enhanced metabolism

Differential metabolism is a major mechanism of plant selectivity to herbicides. Herbicides can be used to control weeds in many crops because the crop is able to metabolise and detoxify the herbicide while the weeds cannot do so. For example, wheat possesses ACCase that is sensitive to the AOPP herbicide diclofop-methyl, but this herbicide can be used to selectively control grass-weeds such as *Avena fatua* (wild oat) and *Lolium* spp. (rye grass) because the herbicide is rapidly metabolised within the crop plants into non-toxic metabolites before it can be transported to the ACCase target site. Several weed biotypes have evolved resistance to herbicides due to an enhanced capacity to metabolise herbicides into non-toxic, or less toxic, compounds. In most cases weeds can already metabolise these herbicides to some degree, but not at a sufficient rate to prevent being killed. Consequently resistant weeds tend to have an *enhanced* ability to metabolise herbicides, and differences between resistant and susceptible plants are quantitative rather than qualitative.

It is sometimes stated that weeds are mimicking crop plants in their ability to metabolise herbicides. In a superficial way this is true, but often there are differences in the mechanisms involved at the biochemical level. For example, safeners are used with the herbicides fenoxaprop-ethyl and clodinafop-propargyl in order to enhance metabolism in wheat plants and thereby improve crop selectivity. Studies on herbicide-resistant *Alopecurus myosuroides* (blackgrass), *Avena* spp. (wild oat) and *Lolium multiflorum* (Italian rye grass) in the UK showed that the presence of the safener had no effect on reducing the activity of fenoxaprop or clodinafop in any of these weeds, despite the resistance of all three being due to enhanced metabolism. Consequently, it appears that the enzymes involved in metabolism of these herbicides in wheat are different from those responsible for resistance in the grass-weeds.

Abutilon theophrasti (velvetleaf) is an example of a small number of species that have evolved resistance to the triazine herbicide atrazine due to an enhanced ability to detoxify the herbicide via glutathione conjugation, as occurs in maize. This metabolic resistance to triazine herbicides has been recorded much less frequently than the target site form of resistance described above.

Populations of *Lolium rigidum* (rigid rye-grass) and *Alopecurus myosuroides* (black grass) have evolved resistance to a wide range of herbicides with different modes of action, including ACCase and ALS inhibitors, phenylurea, triazines and dinitroanilines. In many populations resistance has been shown to be due, at least in part, to an enhanced ability to metabolise herbicides. The critical factor appears to be the degree to which the herbicide can be metabolised, and hence detoxified. This is more dependent on molecular structure than on the conventional classification of herbicides. Thus within one herbicide group (e.g. cyclohexanediones), resistance may occur to one herbicide (tralkoxydim) but not to another (sethoxydim), despite both herbicides having the same mode of action. Populations differ in their ability to metabolise herbicides and different herbicides are often affected to different degrees. Consequently a very complex situation exists.

The involvement of cytochrome P450 mono-oxygenases (P450s) and glutathione-*S*-transferase (GST) enzymes has been implicated in enhanced metabolism of herbicides in several resistant weed species. The P450s comprise a large group of enzymes and there is some evidence that different P450s metabolise different herbicides. However, it is unlikely that the metabolism of any herbicide will involve only one P450 and there is no reason to assume that the same P450s will necessarily be involved in different species, or even different populations of the same species. The regulation of P450s in plants is poorly understood. The first plant P450 gene was sequenced in 1990 and over 500 such genes have now been described. However, the function of the majority of known P450 genes is unknown.

Although most cases of enhanced metabolism have been associated with enhanced cytochrome P450 mono-oxygenase or glutathione-*S*-transferase activity, other enzymes may also be involved. For example, *Echinochloa colona* (jungle-rice) and *Echinochloa crus-galli* (barnyard-grass) have evolved resistance to propanil due to increased aryl acylamidase activity. It is probable that further investigations will show that many other enzymes are involved with conferring herbicide resistance. The genetic and molecular basis of enhanced metabolism resistance is poorly understood at present.

Other mechanisms

Although target site resistance and enhanced metabolism are the best documented mechanisms of resistance, several other mechanisms have been identified. For example, compartmentation has been suggested as a possible resistance mechanism. Compartmentation may be achieved by storage of either the herbicide or its toxic metabolites in the cell vacuole or their sequestration in cells or tissues remote from the site of action. Sequestration of the herbicide, thus excluding it from the site of action in the chloroplast, has been suggested as one of the major mechanisms of resistance to the bipyridilium herbicide paraquat, although alternative explanations, such as rapid enzymic detoxification, have also been suggested. Some herbicides are formulated and applied as pro-herbicides, and are converted into the herbicidally active form within the plant. Lack of conversion of the pro-herbicide within plants could be a mechanism of resistance. There is evidence that resistance to the aryloxyphenoxypropionate esters (e.g. fenoxaprop-ethyl) and the thiocarbamate, triallate, can occur in this manner, although other mechanisms of resistance to the AOPP herbicides are more common. Reduced uptake and translocation to the site of action has often been cited as a possible mechanism of resistance. This has been demonstrated in a few instances (e.g. with paraquat) but it does not seem to be a major mechanism of resistance generally. Recently, evolved resistance to glyphosate was identified in the grass weeds *Lolium rigidum* (rigid rye grass) in Australia and *Eleusine indica* (goosegrass) in Malaysia. Resistance in *Eleusine indica* appears to be due to target site modifications. However, despite a considerable research effort, the mechanism of resistance to glyphosate in *Lolium rigidum* remains unknown.

Cross-resistance patterns and resistance mechanisms: a case study

An example of the complexity of cross-resistance is shown in Fig. 11.3. This shows results for two herbicides evaluated for activity on ten UK populations of *Avena* spp. (wild oat) in a glasshouse dose response assay. ED_{50} values (herbicide

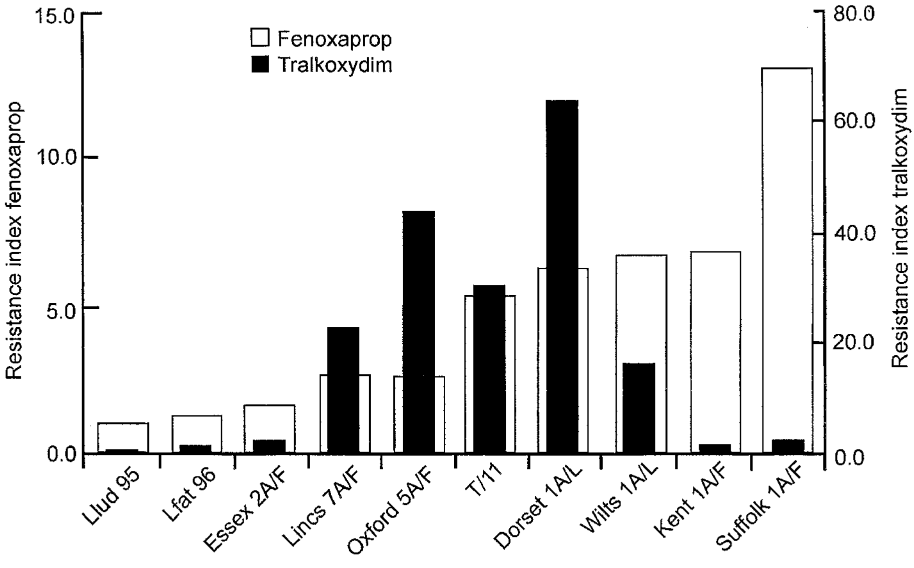

Fig. 11.3 Cross-resistance patterns in ten populations of *Avena* spp. (wild oats).

dose required to reduce foliage fresh weight by 50% relative to untreated plants) were calculated and then expressed as resistance indices. These are the ratios of ED_{50} values relative to the susceptible standard, LLUD 95, and permit comparison of the degree of resistance among the populations – the higher the resistance index, the greater the resistance in that population.

Populations are arranged in order of resistance to fenoxaprop, an AOPP herbicide. It is clear that there is a continuum of response from susceptible at the left to highly resistant at the right. It is not possible simply to place populations into distinct 'resistant' or 'susceptible' categories, and this is true for all resistant grass-weeds in the UK. These differences are not due simply to a different proportion of highly resistant individuals in the populations.

Tralkoxydim is a cyclohexanedione herbicide, and has the same mode of action as fenoxaprop – they are both ACCase inhibitors. However, it is clear that resistance to fenoxaprop is not directly correlated with resistance to tralkoxydim: the two populations most resistant to fenoxaprop are both susceptible to tralkoxydim. In contrast, the intermediate populations show resistance to both herbicides. How can this be explained in terms of the resistance mechanisms?

Biochemical studies showed that the population with the greatest resistance to fenoxaprop (Suffolk 1A/F) possessed an insensitive ACCase – it was target site resistant. This was specific to the AOPP herbicide fenoxaprop and did not confer cross-resistance to the CHD herbicide tralkoxydim. In contrast, the two intermediate populations studied (T/11 and Dorset 1A/F) both had an enhanced ability to metabolise fenoxaprop, and it appeared that this also extended to tralkoxydim. Consequently there was cross-resistance to both herbicides in these populations. Enhanced metabolism and target site resistance did not occur in the same populations, although there is no reason to suppose that these two mechanisms should be mutually exclusive.

From a practical point of view, control of the target site resistant population, Suffolk 1A/F, can be achieved, at least in the short term, simply by changing from fenoxaprop to another herbicide, for example tralkoxydim. Tralkoxydim should give good control even though it has the same mode of action as fenoxaprop. In contrast, populations with enhanced metabolism pose more of a dilemma. Although they only show partial resistance, this does extend to both herbicides, and indeed to others with completely different modes of action (e.g. imazamethabenz, an ALS inhibitor, and flamprop-M-isopropyl). Reasonable control of these intermediate populations can be achieved by applying herbicides to which there is partial resistance at an early timing, when plants have only two or three leaves. Later applications to such populations fail badly, whereas susceptible populations are still well controlled. The question arises of how quickly resistance will continue to evolve if the same herbicides continue to be used: in effect, how quickly populations move from the left to the right-hand side of Fig. 11.3. This is clearly of importance in the longer-term control of such populations. Evidence so far indicates that enhanced metabolism-based resistance evolves slowly whereas target site resistance can build up much faster.

The results highlight the importance of evaluating resistance in a range of populations. If only highly resistant ones are studied, mechanisms conferring partial resistance are likely to be missed. Evidence in the UK is that most populations show partial, rather than absolute, resistance, and basing practical management advice purely on research conducted on highly resistant populations would be misleading, as the example above demonstrates. It must also be recognised that other cross-resistance patterns can occur. For example, in North America there are populations of *Avena* spp. which show target site resistance to AOPP and CHD herbicides. Although not detected in the UK so far, there is no reason to suppose that they do not exist there.

The important lessons from this case study are:

- resistant populations can vary considerably in their degree of herbicide insensitivity;
- different cross-resistance patterns can exist within the same species;
- resistance does not automatically extend to all herbicides with the same mode of action;
- knowledge of the biochemical basis of resistance can help explain whole-plant responses;
- the type of the resistance mechanisms can influence the rate of evolution of resistance.

How does resistance develop?

There are two ways in which resistance may arise within a weed population. Firstly, a major gene or genes conferring resistance may be present at a very low frequency because of random mutations. Such mutations may have occurred before the introduction of a herbicide, so that resistance pre-exists within the population, or they may occur randomly after the herbicide is introduced. In either case, the herbicide kills the majority of susceptible plants but allows resistant individuals to survive and reproduce. Gradually the proportion of resistant individuals in the population increases until a failure to control weeds in the field is first recognised, typically when 10–20% of weeds fail to be killed. It is important to appreciate that the proportion of resistant genes within the whole population is likely to have been increasing for many years before a problem is recognised as a control failure in the field. Target site resistance is usually monogenic and resistance absolute, such that resistant plants are unaffected by the herbicide. In this case, the degree of resistance in the population is dependent on the relative proportion of resistant to susceptible individuals.

Secondly, by a less well recognised process, selection may act on continuous or quantitative variation and achieve a gradual, progressive increase in resistance over several generations. Such quantitative variation may be conferred by a number of polygenes, each of which has a small effect but which collectively produce a polygenic phenotypic trait. In this second method, selection may be acting on resistance genes which are common in the population, albeit ones which individually confer a relatively small advantage. Quantitative variation usually means that there will be a continuum of response to herbicide within a population, from susceptible through partially resistant to highly resistant individuals. In this case, resistance is due to a *progressive* shift or increase in level of resistance in the whole population, rather than to an increase in the proportion of very resistant individuals.

Enhanced metabolism is generally considered to be conferred by polygenic inheritance. As the proportion of alleles conferring enhanced metabolism increases, and genetic recombination occurs over successive generations, there will be a gradual increase in the resistance of the whole population, but with considerable variation in the response of individual plants to herbicides. The rate of evolution of resistance is likely to be slower where inheritance is polygenic than when it is based on a single gene (monogenic), at least when resistance alleles are dominant.

Weeds become resistant to more than one group of herbicides either because there are independent mutations and selection by two or more herbicides to which the species has been exposed, or because there is cross-resistance so that selection by one group of herbicides confers resistance to herbicides with different biochemical modes of action.

Application of a herbicide will select for any trait that favours the survival of individual plants. Many of these traits are likely to confer only a modest advantage so may be of little consequence in the short term. Other traits may endow a high degree of resistance, and these are more likely to impact on field activity of herbicides – and be investigated. However, it is important to recognise that plants may survive because of the presence of a wide range of different resistance mechanisms, and these may well differ between populations of the same species, as well as between species.

While the mechanisms outlined above have been shown to have a big impact on herbicide activity in resistant plants, there are almost certainly many other mechanisms yet to be recognised which may impact to a greater or lesser extent on herbicide activity. Some of these may evolve quite slowly, yet in time become of major consequence, whereas others may remain of minor significance.

Evolution of resistance

The following factors are generally considered to be of particular importance in the development of herbicide resistance and will be discussed:

(1) The initial frequency of the resistance trait
(2) Genetic basis of resistance
    (a) Number of gene/alleles involved

  (b) Degree of dominance of resistance alleles
  (c) Mode of inheritance
  (d) Reproductive/breeding characteristics
(3) Selection pressure
(4) Fitness differences
(5) Seed bank in the soil

The initial frequency of the resistance trait

Resistant genotypes may be present in plant populations in varying, but low, frequencies before any exposure to herbicides, or they may arise by random mutation. There is no evidence that herbicides cause such mutations, and the concept of directed (i.e. non-random) mutation is controversial. Resistance should not be viewed as inevitable. It is probable that in many cases resistance genes simply do not exist within a population and this may explain why resistance has often evolved in one, or at most a few, species within a weed community, despite all being exposed to the same intensity of herbicide use (e.g. triazine resistance).

The development of resistance as a problem on a field scale is dependent on the increase in the proportion of the resistant genotypes within the population. The initial frequency of resistance in unselected populations has been estimated to be between $10\ ^{5}$ and $10\ ^{12}$. Detecting resistant plants at such low frequencies in unselected populations is very difficult, and there is little direct experimental evidence to support such estimates. Frequencies are likely to vary with plant species, locality and type of resistance, so it is very difficult to predict the initial frequency of a resistant genotype in any particular weed population. However, weed seed banks for individual species can be very high (over 50 000 seeds/m^2 in extreme cases), and even a modest seedbank of 10^3 seeds/m^2 represents 10^7 seeds in each hectare. Thus, even with the very low estimates of initial frequency of resistant individuals given above, there is a high probability of resistance occurring in a relatively small area, as a consequence of the vast numbers of weed-seeds that exist in the seed bank. Clearly, the probability of resistance occurring within any given area is greater at high than at low weed infestations. However, the vast majority of seeds die in the soil and never produce a plant that goes on to reproduce, so this reduces the *effective* initial frequency of resistance considerably.

The potential rate of population increase per annum varies considerably between weeds, but increases of ten-fold per annum are not atypical. Consequently resistant individuals present at seemingly insignificant frequencies have the potential to increase to levels which impact on crops within a relatively short space of time. Thus a population density of 100 weeds/m^2 equates to a density of 10^6 weeds/ha^2. If one weed per hectare is resistant (i.e. 1 in 10^6) and weeds increase ten-fold per annum, then after six years there will be potentially 10^6

resistant weeds/ha[1]. In practice intraspecific competition is likely to have a large influence on the actual number of plants surviving.

Genetic basis of resistance

Genetic studies indicate that most target site resistance is conferred by single nuclear genes, with resistant alleles showing a high degree of dominance. However, there is evidence that a range of inheritance traits can occur, including complete dominance of resistance alleles (e.g. paraquat resistance in *Erigeron canadensis*, Canadian fleabane), incomplete dominance (e.g. ALS resistance in *Lactuca serriola*, prickly lettuce), recessive resistance alleles (e.g. trifluralin resistance in *Setaria viridis*, green foxtail), non-nuclear, maternal inheritance of chloroplastid DNA (e.g. most cases of triazine resistance) and polygenic inheritance (e.g. multiple-herbicide resistance in *Alopecurus myosuroides*, blackgrass).

In contrast to virtually all other documented cases of resistance, triazine resistance is not inherited via chromosomal DNA in the nucleus, but by maternal inheritance of non-nuclear DNA in the chloroplasts. An important consequence of this is that resistance genes are not transmitted in pollen, but that all seeds of a resistant plant will produce resistant individuals.

The degree of dominance of resistance genes is particularly important for outcrossing weed species because fully recessive genes will tend to be diluted into heterozygous individuals by the larger number of susceptible alleles. In contrast, the level of dominance has less impact on the evolution of resistance for a species that is entirely self-pollinating, because among progeny of individuals carrying a resistance gene there will always be some that are homozygous for that gene.

The genetic basis of resistance will affect the rate at which resistance builds up at the population level. With random mating, at low gene frequencies a dominant allele will spread faster than a recessive one. The much longer time taken by recessive alleles to reach appreciable frequencies means that resistance endowed by these genes is less likely to evolve. Very few cases of resistance conferred by recessive alleles have been identified.

The extent to which a species is an obligate cross-pollinator, compared with being self-pollinated, can strongly determine the genotypic structure of a population. In theory, the spread and subsequent recognition of herbicide resistance will occur more rapidly in cross-pollinated populations, assuming resistance is associated with a single dominant allele and cross-pollination is as efficient as self-pollination.

It has been postulated that high doses of herbicide favour selection of single gene based target site resistance, whereas lower doses, or less effective herbicides, favour polygenically based resistance, such as enhanced metabolism. The theory is that high doses of highly active herbicides kill virtually all susceptible plants, leaving only highly resistant individuals with target site resistance, which is usually inherited monogenically. In contrast, the response to selection based on polygenes depends on genetic recombination, with several genes each contributing in a minor way to the total genotype. In this case, selection will be favoured by herbicide applications which allow partially resistant plants to survive as this will select for genotypes showing elevated levels of resistance as individual polygenes become combined within a genotype. If high rates were applied, there is a likelihood that those genotypes with a slightly enhanced level of resistance would be killed, and consequently the frequency of recombinations of polygenes would be greatly reduced and selection for resistance diminished.

Selection pressure

This is probably the most important factor determining the evolution of resistance and can be defined as the relative proportion of resistant and susceptible individuals remaining after herbicide treatment. The highest selection pressure will exist when all susceptible plants are killed and all resistant plants are unaffected by herbicide. No selection pressure will exist in the absence of a differential kill of resistant and susceptible individuals. Selection pressure depends on the:

- frequency of herbicide use
- persistence of the herbicide
- pattern of weed emergence
- intrinsic activity of the herbicide
- specificity of the herbicide

Repeated use of the same herbicide, or one with the same mode of action, is likely to impose a greater selection pressure than the use of rotations of herbicides with different modes of action. If there is no resistance to the alternative herbicides, there will be no differential selection, and hence the evolution of resistance is likely to be delayed. However, enhanced metabolism-based resistance, where resistance may extend to many different herbicides with different modes of action, with a wide range of different herbicides may impose the same selection pressure. The outcome will depend on the exact nature of enhanced metabolism and vulnerability to different herbicides.

Applications of herbicides with considerable residual activity (such as atrazine) are considered to impose a high selection pressure because successive flushes of germinating weeds are exposed to the herbicide, and consequently the surviving weed population contains a high proportion of resistant individuals. The widespread and rapid evolution of resistance to ALS inhibitors, such as the sulphonylurea herbicide chlorsulfuron, has also been attributed to the long persistence of some members of this herbicide group. However, resistance has evolved just as rapidly to ACCase inhibitors such as diclofop-methyl which have little or no residual activity in the soil. If persistence is really of critical importance, it might be expected that resistance would evolve fastest in those weeds most sensitive to the herbicide. These would still be subject to selection by the small amounts of herbicide persisting in the soil long after application. There is little evidence for this, although there are many other factors influencing resistance.

If weeds emerge in a single flush prior to herbicide application, herbicide persistence is of no consequence as all plants are exposed to the herbicide. With protracted germination patterns, many more weeds will be exposed to the herbicide if it persists in the soil than if a foliar-acting herbicide, with no residual activity, is used early in the period of weed emergence. Even if a herbicide has no soil residual activity (e.g. paraquat), frequent applications will expose successive flushes of seedlings to selection. In some horticultural situations resistance has evolved due to over-frequent applications of paraquat.

A highly active herbicide will kill all susceptible plants, leaving only resistant individuals, whereas a moderately active herbicide may allow many susceptible individuals to survive and reproduce, thus imposing a lower level of selection. A herbicide with no activity on an individual species will impose no selection pressure. Many farmers use reduced rates of herbicide; this is likely to result in reduced herbicide efficacy, which may result in a difference in selection pressure compared with that using recommended rates. It was argued earlier in this section that high rates favour target site resistance by allowing only highly resistant individuals to survive, whereas reduced rates favour enhanced metabolism resistance by allowing the survival of partially resistant individuals which would have been killed by higher rates. There has been considerable debate about whether high rates or low rates encourage herbicide resistance more, but the matter remains unresolved. There can be no simple general answer, as the intrinsic efficacy of different herbicides varies so much between individual weeds that it is difficult to quantify what is meant by high or low rates. There may well be individual cases where either high or low rates of herbicides can be shown to encourage resistance in a specific weed (but there are very few convincing examples), but these should not be interpreted as being indicative of a general concept. Too many other factors are involved and the high rate versus low rate debate is best considered one which has no simple answer.

A herbicide which is only active on a very limited range of weeds (e.g. difenzoquat on *Avena* spp., wild oat), will clearly only pose a selection pressure on those few species which are susceptible. In contrast, broad-spectrum herbicides (e.g. atrazine, chlorsulfuron) will impose selection pressure on a much wider range of species, and these may include some which initially are not major target species. Use of such herbicides can potentially transform species of minor importance into resistant weeds of major importance.

Fitness

Fitness is generally defined as reproductive success, or the proportion of genes an individual leaves in the gene pool of a population. The two fundamental components of fitness are survival and reproduction. Critical comparison of the reproductive success of individual plants in the field environment is difficult.

Consequently many studies relating to resistant weeds have concentrated on the evaluation of parameters which are easier to determine, such as growth rate or biomass production, as indicators of fitness differences. However, few inferences are possible about the overall fitness of a resistant biotype relative to a susceptible one from growth and biomass studies alone. Reduced fitness of resistant weeds is sometimes assumed to be a general phenomenon and an intrinsic feature of the herbicide resistance trait. It has been stated that fitness penalties must exist with any target site based resistance: otherwise, if resistant mutations were neutral or very near neutral, there would be naturally resistant populations due to random genetic drift and pre-existing the use of herbicide. Certainly many triazine-resistant weeds do show reduced vigour in comparison with susceptible biotypes of the same species. Reduced photosynthetic efficiency, associated with the alterations in the herbicide binding site in the chloroplasts, is considered to be the reason for the lower photosynthetic potential and reduced fitness of triazine-resistant plants. However, many studies of other resistant weeds have failed to demonstrate a clear fitness penalty associated with resistance. Fitness experiments are difficult to conduct and rarely include all components of the weed life cycle. It does appear that with most resistant weeds, fitness penalties are small and in many cases undetectable. Statistically non-significant differences may well play a major role in the long-term rate of selection and deselection of resistance. This remains a controversial topic.

Seed bank in the soil

The seed bank in the soil can exert a strong ‘buffering’ influence which can delay the rate of enrichment for resistance (Chapters 3 and 4). The importance of this reserve of unselected, or less selected, genetic material depends largely on the persistence of seeds in the soil, the germination characteristics of the weed and the cultivation system used before establishing the crop. In the absence of cultivation, weed-seedlings may be largely derived from seeds shed in the previous crop. Consequently there will be little ‘buffering’ from old seeds. In contrast, cultivations such as ploughing will bury most freshly shed seeds, but transfer older seeds closer to the soil surface. This favours germination and successful seedling emergence from these older seeds, and hence there will be a greater ‘buffering’ effect.

Modelling

Attempts have been made to develop models which integrate the genetic, ecological and physiological processes involved in the evolution of herbicide-resistant populations. Such models highlight the relative importance of factors controlling the development and spread of herbicide resistance. The models, in general, relate to resistance inherited on one, or at most a few, major genes. However, most of the principles embodied in the models should also be relevant to resistance inherited polygenically.

The model of Gressel & Segal (1990) estimates the increase in proportion of resistant plants over time in a population, based on the initial frequency of the resistant genotype, the selection pressure imposed by the herbicide, its relative ecological fitness compared with susceptible types in the absence of herbicides and the longevity of the seed bank in the soil. The model of Maxwell *et al.* (1990) stresses the importance of two major processes that determine the dynamics of herbicide resistance. Firstly, processes such as survival and fecundity, both influenced by plant competition, affect the fitness of resistant biotypes relative to that of the susceptible biotype. Secondly, processes that contribute to gene flow in space and time, such as immigration of pollen and seeds, seed dormancy and type of breeding system, alter the frequencies of resistant and susceptible alleles in a population.

In spite of the differences between the two models in emphasising the relative importance of specific biological processes, their predictions are similar. Both models show that selection pressure must be reduced to prevent the development of resistance, but differ in their proposed strategies to achieve this.

Recently an attempt was made to model different cultivation and herbicide strategies for their effect on herbicide resistance by incorporating several resistance factors into a comprehensive life cycle model. A single dominant mutation conferring resistance to AOPP and CHD herbicides was incorporated into a quantitative model for the population development of *Alopecurus myosuroides* (blackgrass). Take an example of an initial seedbank of 100 seeds/m^2, one in 10^6 of which mutates to resistance each generation, and management involving annual use of AOPP/CHD herbicides which kill 90% of susceptible plants but no resistant ones. From this initial state the model predicts that a threshold of 10 plants/m^2 surviving herbicide application ('field resistance') will develop in nine to ten years if all tillage is by tine cultivation to a depth of 10 cm; or in 28–30 years of annual ploughing; or in 12 years if tine cultivations are interspersed with ploughing once every four years (Fig. 11.4).

If AOPP/CHD herbicides are alternated with herbicides with different modes of action, outcomes depend on the annual kill rate: with 95% kill (of susceptible plants by AOPP/CHDs and of all plants by alternative herbicides) and tine cultivation, field resistance develops in 22 years. However resistance can be delayed for 45 years if AOPP/CHDs are rotated with two additional herbicides, each with a different mode of action. The model predictions on the number of years required for field resistance to develop are not highly sensitive to the density of the seed bank or the initial frequency of resistance.

Models indicate what is possible, and what will happen if certain conditions are met. In many cases, assumptions are based on very limited data and rarely are predictions from models tested against observations from the field. There is a

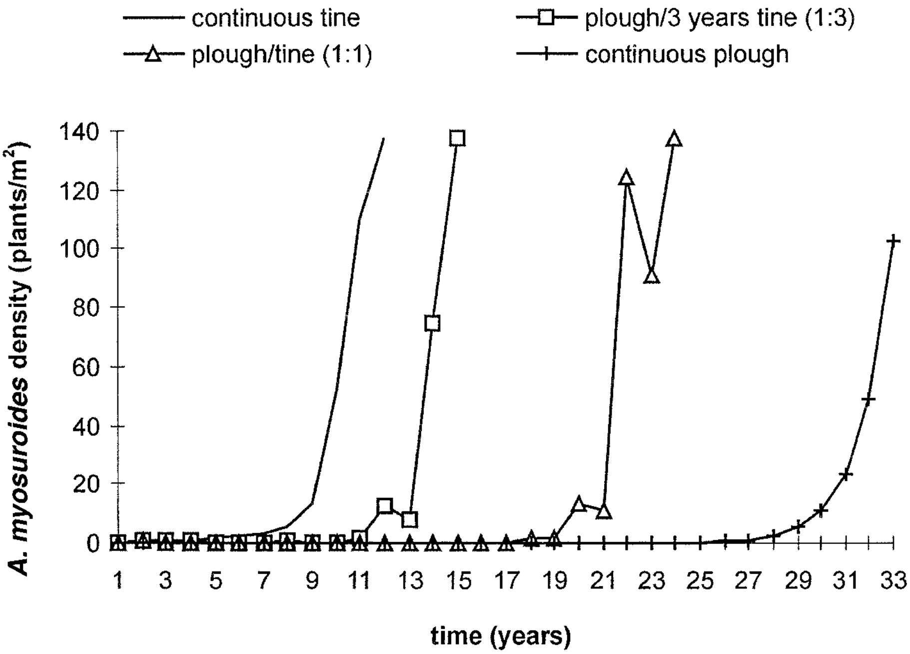

Fig. 11.4 Predicted effect of different cultivation regimes on the build-up of *Alopecurus myosuroides* (black grass) when aryloxypropionate/cyclohexanedione herbicides are applied each year achieving 90% kill of susceptible plants.

need to analyse critically the predictions from models to assess their precision. In this way a better understanding of the critical factors determining the development of resistance may be obtained.

Prevention and management of herbicide resistance

Worldwide experience has been that farmers tend to do little to prevent herbicide resistance developing, and only take action when it is a problem on their own farm or neighbour's. Careful observation is important so that any reduction in herbicide efficacy can be detected. This may indicate evolving resistance. It is vital that resistance is detected at an early stage as if it becomes an acute, whole-farm problem, options are more limited and greater expense is almost inevitable. Table 11.3 lists factors which enable the risk of resistance to be assessed.

An essential pre-requisite for confirmation of resistance is a good diagnostic test. Ideally this should be rapid, accurate, cheap and accessible. Many diagnostic tests have been developed, including glasshouse pot assays, petri dish assays and chlorophyll fluorescence. A key component of such tests is that the response of the suspect population to a herbicide can be compared with that of known susceptible and resistant standards under controlled conditions.

Table 11.3 Agronomic factors influencing the risk of herbicide resistance development

Factor	Low risk	High risk
Cropping system	Good rotation	Crop monoculture
Cultivation system	Annual ploughing	Continuous minimum tillage
Weed control	Cultural only	Herbicides only
Herbicide use	Many modes of action	Single mode of action
Control in previous years	Excellent	Poor
Weed infestation	Low	High
Resistance in vicinity	Unknown	Common

Most cases of herbicide resistance are a consequence of the repeated use of herbicides, often in association with crop monoculture and reduced cultivation practices. It is necessary, therefore, to modify these practices in order to prevent or delay the onset of resistance or to control existing resistant populations. A key objective should be the reduction in selection pressure. An integrated weed management (IWM) approach is required, in which as many tactics as possible are used to combat weeds (Chapter 14). In this way, less reliance is placed on herbicides and so selection pressure should be reduced.

Cultural control methods

Many non-herbicidal methods of weed management can be used to reduce weed populations. These methods will not be appropriate in all situations and individual circumstances will dictate which are the most practicable. Provided that susceptible and resistant plants respond similarly, there should be no selection in favour of resistant individuals. If resistant plants are less ‘fit’ than susceptible plants, e.g. by being smaller, they may be controlled relatively more effectively by cultural control measures and deselection may occur. However, clear fitness differentials may be limited to certain types of resistance, e.g. triazine resistance.

Cultivations

Non-inversion tillage maximises the proportion of the weed population derived from seeds shed in the previous crop because seeds are retained close to the soil surface. This minimises the probability of back-crossing with earlier, less selected generations derived from older, buried seeds. Inversion tillage, such as mouldboard ploughing, can bury most freshly shed seeds to a depth from which seedlings of most weeds are unlikely to emerge (>5 cm).

Inversion tillage has two distinct benefits: firstly, it may reduce substantially the population of some weeds; and secondly, it can increase the proportion of susceptible individuals by increasing the number of seedlings derived from older, less selected seeds. The greater the seed longevity and depth of emergence, the lesser the beneficial effects on population size. However, greater seed persistence may improve changes to the susceptible/resistant ratio, especially if inversion tillage follows a period of minimum cultivation.

In some situations annual ploughing is not feasible because of cost or environmental constraints, but rotational ploughing once every four to five years may be an acceptable alternative. Such a strategy may be a method of returning the genetic structure of the population to that which existed several years previously. This strategy could be detrimental in situations where resistance has been managed successfully for several years before the ploughing.

In-crop cultivations such as inter-row hoeing or harrowing are established methods of weed management. The feasibility and effectiveness of these techniques is dependent on the individual weed species and the crop being grown.

Crop rotation

Many annual weeds are strongly associated with specific crops, so crop rotations can reduce the intrinsic success of such weeds and may permit the use of alternative herbicides and cultural control measures (e.g. inter-row hoeing in row crops). The inclusion of a grass ley in an arable rotation can also be an effective means of reducing populations of many arable grass-weeds, providing seed return is prevented. Crop rotation may reduce the overall usage of herbicides and extend the range of active ingredients available.

Set-aside/fallowing

Fallowing is a traditional method of weed management, although land is taken out of production. 'Set-aside', and similar schemes in which farmers are paid not to crop the land, also provide an opportunity to reduce weed populations. Growers may be unwilling to accept the cost of weed management on a 'crop' which gives low (set-aside) or no (fallow) financial returns. However, failure to prevent seed return in fallow or 'set-aside' land may lead to increased weed problems in subsequent crops (see Chapters 3 and 4).

Burning crop residues

Burning (where and when allowed) can destroy up to 80% of freshly shed seeds lying on the soil surface. In addition, it can break the dormancy of some surviving seeds and the emerging seedlings may then be destroyed before the next crop is sown.

Stubble hygiene

It is important that all weed seedlings that have emerged before crop sowing or planting are destroyed, otherwise some may re-establish in the crop. This may be achieved either by effective seedbed cultivations or by using non-selective herbicides such as glyphosate.

Delayed drilling

Delayed drilling allows more time for weed-seedling emergence to occur before the crop is sown. This may be used in association with shallow stubble cultivations to encourage germination by producing a 'false' or 'stale' seedbeed. This technique can be particularly effective with weeds that have a relatively short period of innate dormancy, provided that there is sufficient moisture to permit seed germination.

Crop competition

Some agronomic practices favour the development of competitive crops which are better able to suppress weeds, e.g. selection of more competitive species or cultivars, higher than normal seed rates, narrower row spacings, improved drainage and good seedbeds to favour rapid crop establishment.

Prevention of seed return

Grazing, cutting or spraying with non-selective herbicides may be possible in some situations. If weeds are restricted to limited areas, preventing seed return may help prevent these patches becoming a whole-field problem. Removal of plants by hand from within crops ('roguing') is feasible for low weed populations, or patches of tall weeds such as *Avena* spp. (wild oat).

Seed recovery at harvest

This is another method of reducing seed return; it has been used in Australia for management of *Lolium rigidum* (rigid rye grass). It involves modification to the harvesting operation, so that weed seeds are diverted into a container rather than being returned to the ground. The seeds can therefore be removed from the field and destroyed. The efficacy of such a technique is very dependent on the time of shedding of weed-seeds relative to the time of crop harvest.

Avoidance of the introduction and spread of resistant seeds and plants

Sowing of contaminated seed should be avoided and the dissemination of seeds and plants in harvesting and cultivation equipment, straw or manure should be avoided.

Other methods

Other techniques such as the use of mulches (Chapter 13), and biological control (Chapter 17) may be feasible alternatives to herbicides in some situations.

Herbicidal control

Alternative herbicides

When resistance is first suspected or confirmed, the efficacy of alternatives is likely to be the first consideration. The use of alternative herbicides which remain effective on resistant populations can be a successful strategy, at least in the short term. The effectiveness of alternative herbicides will be highly dependent on the extent of cross-resistance. If there is resistance to a single group of herbicides, then the use of herbicides from other groups may provide a simple and effective solution, at least in the short term. For example, many triazine-resistant weeds have been readily controlled by the use of alternative herbicides such as dicamba or glyphosate. If resistance extends to more than one herbicide group, then choices are more limited.

It should not be assumed that resistance will automatically extend to all herbicides with the same mode of action, although it is wise to assume this until proved otherwise. For example, some (but not all) populations of *Avena* (wild oat) and *Lolium* spp. (rye grass) with target site resistance (insensitive ACCase) show resistance to aryloxyphenoxypropionate but not to cyclohexanedione herbicides, despite both groups being ACCase inhibitors. In many weeds the degree of cross-resistance between the five groups of ALS inhibitors varies considerably. Much will depend on the resistance mechanisms present, and it should not be assumed that these will necessarily be the same in different populations of the same species.

These differences are due, at least in part, to the existence of different mutations conferring target site resistance. Consequently, selection for different mutations may result in different patterns of cross-resistance. Enhanced metabolism can affect even closely related herbicides to differing degrees. For example, populations of *Alopecurus myosuroides* (blackgrass) with an enhanced metabolism mechanism show resistance to pendimethalin but not to trifluralin, despite both being dinitroanilines. This is due to differences in the vulnerability of these two herbicides to oxidative metabolism. Consequently, care is needed when trying to predict the efficacy of alternative herbicides.

Mixtures and sequences

The use of two or more herbicides which have differing modes of action can reduce the selection for resistant genotypes. Ideally, each component in a mixture should:

- Be active at different target sites
- Have a high level of efficacy
- Be detoxified by different biochemical pathways
- Have similar persistence in the soil (if it is a residual herbicide)
- Exert negative cross-resistance
- Synergise the activity of the other component

No mixture is likely to have all these attributes, but the first two listed are the most important. There is a risk that mixtures will select for resistance to both components in the longer term. One practical advantage of sequences of two herbicides compared with mixtures is that a better appraisal of the efficacy of each herbicide component is possible, provided that sufficient time elapses between each application. A disadvantage with sequences is that two separate applications have to be made and it is possible that the later application will be less effective on weeds surviving the first application. If these are resistant, then the second herbicide in the sequence may increase selection for resistant individuals by killing the susceptible plants which were damaged but not killed by the first application, but allowing the larger, less affected, resistant plants to survive. This has been cited as one reason why ALS-resistant *Stellaria media* has evolved in Scotland recently (2000), despite the regular use of a sequence incorporating mecoprop, a herbicide with a different mode of action.

Herbicide rotations

Rotation of herbicides from different chemical groups in successive years should reduce selection for resistance. This is a key element in most resistance prevention programmes. The value of this approach depends on the extent of cross-resistance, and whether multiple resistance occurs owing to the presence of several different resistance mechanisms. A practical problem can be the lack of awareness by farmers of the different groups of herbicides that exist. In Australia a scheme has been introduced in which identifying letters are included on the product label as a means of enabling farmers to distinguish products with different modes of action.

Herbicide management

Optimising herbicide input to the economic threshold level should avoid the unnecessary use of herbicides and reduce selection pressure. Herbicides should be used to their greatest potential by ensuring that the timing, dose, application method, soil and climatic conditions are optimal for good activity. In the UK, partially resistant grass weeds such as *Alopecurus myosuroides* (blackgrass) and *Avena* spp. (wild oat) can often be controlled adequately when herbicides are applied at the 2–3 leaf stage, whereas later applications at the 2–3 tiller stage can fail badly. Patch spraying, or applying herbicide to only the badly infested areas of fields, is another means of reducing total herbicide use. Application techniques are considered in Chapter 10 and optimisation of herbicide performance in Chapter 16.

Synergists and safeners

Although the practical implementation of synergists in weed management programmes is very limited at present, this approach may be particularly appropriate in cases where resistance is due to enhanced metabolism, although it is important that herbicide selectivity in the crop is not compromised. The application of propanil in mixture with the organophosphate herbicide piperophos has proved a useful management tool for propanil-resistant *Echinochloa colona* (jungle-rice) in Costa Rica. Piperophos synergises the activity of propanil by inhibiting aryl acylamidase activity, which is responsible for enhanced metabolism of propanil in resistant plants.

Spray topping

This involves the application of herbicides at a late stage of weed growth with the objective of reducing viable seed return rather than killing plants. In Australia, spray topping of *Lolium rigidum* (rigid rye grass) and *Avena* spp. (wild oat) is practised as a means of reducing seed return.

Genetically modified herbicide-resistant crops

These could permit the use of total herbicides, such as glyphosate, for control of weeds resistant to other herbicides. Glyphosate has been used very extensively worldwide since the 1970s and used to be considered to be very low risk in terms of resistance. However, glyphosate-resistant *Lolium rigidum* (rigid rye grass) evolved in Australia in 1996 and *Eleusine indica* (goosegrass) in Malaysia in 1997. This demonstrates whereas while glyphosate is 'low risk', it is not 'no risk'. Herbicide-resistant crops could encourage the repeated use of glyphosate, which may favour the development of resistant biotypes more widely. Herbicide resistant crops will need to be used with care if they are to reduce, rather than increase, the risk of evolution of herbicide resistance in weeds.

Conclusions

Herbicide resistance needs to be kept in perspective. Whereas some resistant weeds unquestionably cause major problems, others are of minor significance and are easily managed. Understandably, there has been a tendency to place most research emphasis on highly resistant populations, as these can result in spectacular herbicide failures in the field. In many such cases resistance is due to an insensitive target site which, whilst giving high degrees of resistance, affects only a single herbicide group. Such populations may be controlled easily by alternative herbicides, assuming they are available.

Mechanisms such as enhanced metabolism, which usually result in reduced, rather than no, herbicide activity, tend to be overlooked and are probably under-recorded. Although the degree of resistance may be lower, resistance can extend to many different herbicide groups, and this is largely unpredictable. This type of resistance, which is probably based on polygenes, tends to evolve slowly but may ultimately be of greater significance because of the effects on a wider range of herbicides. There are almost certainly other, as yet unrecognised, mechanisms of resistance.

The real significance of many of the theoretical concepts covered within this chapter remains unresolved or controversial. Theoretical considerations are a useful starting point, and should not be ignored, but they are no substitute for careful field experimentation. There is a need to challenge the theoretical concepts and not to accept them blindly, and to conduct more research which is directly related to the practical problems of resistance.

Herbicide resistance has evolved because too much reliance has been placed on herbicides to control weeds. It is clear that a more broadly based approach to weed management is needed in which herbicide use is integrated with non-chemical methods of weed management. It is vital that the very considerable research effort worldwide produces sound practical solutions. Strategies for resistance prevention and management are of no use unless they are implemented. It is essential that technology transfer initiatives are developed to ensure the effective communication of practical advice to farmers and growers.

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Chapter 12
Herbicide-Tolerant Crops

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Introduction

Herbicide-tolerant crops, especially those tolerant to glyphosate, represent the next revolutionary breakthrough in weed control. Their use has created opportunities for farmers and growers to apply certain total herbicides but achieve selective weed control. These compounds control a range of broad-leaf and grass weeds, without harming the crop in which tolerance has been engineered.

Novel methods of biotechnology have been applied to the production of herbicide-tolerant crops (HTCs). New technology, involving tissue culture, pollen selection or gene transfer, has enabled the development of tolerant varieties from proven but susceptible varieties. This has made possible the use of herbicides which are preferable from agronomic, environmental or genetic viewpoints. The benefits and disadvantages arising from the use of HTCs include the following:

Advantages
- Improved yield through good weed control
- Improved quality through removal of existing volunteers of the same species;
- Improved unit cost of production
- The possibility of using low-tillage systems

Disadvantages
- The danger of cross-pollination and consequence stacking (pyramiding) of genes endowing tolerance
- The potential for development of herbicide-tolerant (HT) volunteers
- The potential of development for herbicide-resistant weeds

This chapter will review the development of HTCs with particular regard to the use of recombinant techniques, the molecular basis of tolerance, mechanisms of weed resistance and the environmental issues arising through their use. Experience gained from the use of HTCs in the USA and Canada will be considered, together with legislation relating to their use in Europe and the UK; particular focus will be applied to oilseed rape, which will probably be the first transgenic crop to be approved for use in the UK.

Recombinant techniques used to achieve herbicide resistance

The techniques used to achieve herbicide tolerance have been reviewed by Cole (1994) and the underlying molecular technology by Finch (1994). Crops which have been transformed to become herbicide-tolerant include those shown in Table 12.1. The expansion of this range of crops is limited by the techniques for gene insertion and the regeneration of intact transgenic crops, particularly in cereals.

Table 12.1 Transformation by crop species for herbicide tolerance*

Herbicide	Novel gene product	Gene function†	Gene source	Transformed agricultural crops
Sulfonylureas	Acetolactate	mts	Higher plant	Chicory, cotton, flax, lettuce, lucerne, melon, sugar beet, tomato
Imidazolinones	Acetolactate synthase	mts	Higher plant	Tobacco
Glyphosate	Enolpyruvylshikimic acid phosphate synthase	mts	Soil and enteric bacterium, higher plant	Rape, soybean, tomato
	Glyphosate oxidoreductase	detox	Soil bacterium	Maize, rape, soybean
Atrazine	'D1' protein	mts	Higher plant	Soybean
Glufosinate	*N*-acetyl transferase	detox	Bacterium	Cotton, lucerne, maize, potato, rape, rice, sugar beet, tomato
	Glutamine synthetase	ots	Higher plant	Tobacco
Bromoxynil	Nitrilase	detox	Soil bacterium	Cotton, potato, rape, tomato
2,4-D	Mono-oxygenases	detox	Soil bacterium	Cotton

* After Cole (1994).
† mts = mutated target site; ots, over-expressed target site; detox = detoxification.

Successful transformation has been effected by the use of the Ti plasmid as the gene vector mediated by *Agrobacterium tumefaciens*. Selection of transformed material has routinely involved the use of identifying kanamycin resistance conferred by the *NPTII* gene carried in tandem on the vector. High-level gene expression is generally facilitated by means of the constitutive cauliflower mosaic virus 35S promoter. This has been used to assist foreign gene expression in recipient plants. Generally, herbicide target sites must also carry sequences which enable correct targeting of the gene product from nucleus to chloroplast. Integration of the herbicide tolerance gene into the host genome is generally confirmed by Southern hybridisation.

In general, the herbicide tolerance gene is expressed as a determinant which is integrated at a single nuclear locus. Tobacco (*Nicotiana tabacum*) has often been used as a model crop to study and optimise alien gene performance; this reflects the ease of transformation in this species.

A general strategy for cloning pesticide resistance genes is portrayed in Fig. 12.1.

Mechanisms of conferring herbicide tolerance in crops

The capacity to transform major crops using genes for herbicide tolerance can provide new uses for specific herbicides and enable enhanced selectivity between crop and weeds. This is achieved by manipulation of the qualities of the crop plant rather than the chemistry of the herbicide (considered in Chapter 8). The techniques used to apply plant molecular genetics to devise HTCs have been described in a recent review by Cole & Rodgers (2000).

Tolerance to herbicides can be achieved by several mechanisms, including target site modification, metabolic detoxification of the herbicide active ingredient or manipulation of the protective responses of plants (Table 12.1).

Target site modifications

5-enol-*Pyruvylshikimate-3-phosphate synthase (EPSPS)*

The engineering of tolerance to glyphosate into crops such as soybean, cotton and maize has perhaps been the most notable achievement of plant biotechnology. Glyphosate was launched as a total herbicide by Monsanto in the early 1970s. Its success is attributable to its control of a wide range of annual and perennial broad-leaf and grass weeds. Its efficacy is due to its systemicity in weeds coupled with benevolent environmental and toxicological properties.

Glyphosate acts by inhibiting the enzyme 5-*enol*-pyruvylshikimate-3-phosphate synthase (EPSPS) which catalyses one step of the shikimic acid pathway prior to the formation of chlorismic acid. It thus inhibits the synthesis of essential amino acids, auxins and a range of secondary products in plants. Its low mammalian toxicity is due to the absence of the shikimic acid pathway in animals. In plants, glyphosate binds to the enzyme, resulting in conformation changes preventing the binding of phosphoenolpyruvate (PEP), which is one of the two substrates of EPSPS.

Studies of the alignment of nucleotide sequences from genes encoding EPSPS

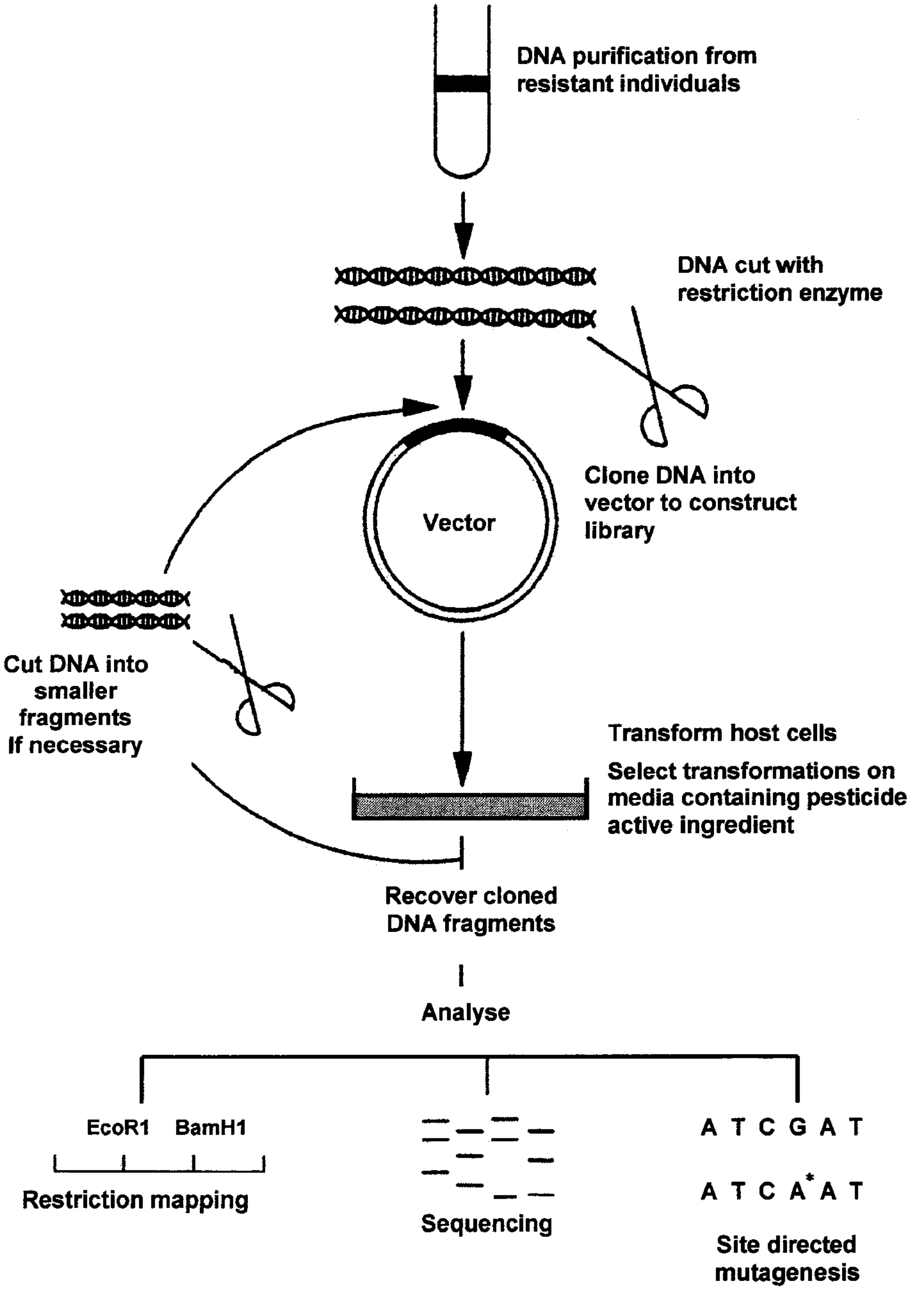

Fig. 12.1 General strategy for cloning pesticide resistance genes. (*After: Holloman & Butters, 1994.*)

from a diverse range of organisms suggested that scope existed to alter the primary structure of the enzymes, making it insensitive to glyphosate. The initial sources of insensitive EPSPS were bacteria which had been subjected to mutagenic agents. The *aro*A gene of a *Salmonella typhimurium* mutant which encodes an insensitive form of EPSPS was used for plant transformation studies. Tolerance to glyphosate was induced in tobacco and tomato plants using a construct containing a promoter from *Agrobacterium tumefaciens*. The degree of tolerance, however, was not sufficient from an agronomic viewpoint. Subsequent ligation of the *aro*A mutant gene with a chloroplast transit peptide coding sequence from *Petunia* EPSPS enabled development of tobacco plants having enhanced tolerance.

Subsequently a naturally occurring EPSPS from *Agrobacterium* sp. strain CP4 was identified which combined exclusion of glyphosate with high affinity for PEP. Using a construct containing two CP4 EPSPS sequences fused to a chloroplast transit peptide, a tolerant soybean cultivar (A5403) was achieved. In field trials a resultant line of soybean containing a single EPSPS and transit sequence was found to be completely tolerant to glyphosate. Tolerance was stable over several generations and crop yield was good. CP4 constructs were also used to develop glyphosate-tolerant cotton. Ultimately, high-performance glyphosate-tolerant plants were achieved by combining the *gox* gene for glyphosate detoxification (via glyphosate oxidoreductase) with CP4 EPSPS. Commercially viable glyphosate tolerance was achieved in maize using a double mutant maize EPSPS fused with a chimeric optimised transit peptide.

Acetolactate synthase

Some of the most widely used herbicides (e.g. sulfonylureas) act by inhibition of the enzyme acetolactate synthase (ALS) (or acetohydroxyacid synthase, AHAS). In plants and micro-organisms ALS catalyses a major step in the formation of branched-chain amino acids. Early studies showed that mutants of micro-organisms and yeast could be obtained which were tolerant of high concentrations of sulphonylurea herbicides. Tolerance was associated with situations where ALS had undergone single amino acid substitution at conserved areas.

Subsequently, tolerance to these herbicides was obtained using the *csrl*-1 mutant gene from *Arabidopsis thaliana* (L.) Heynh. This gene encoded an inhibitor-insensitive ALS with a single predicted proline-to-serine substitution; its use has resulted in a number of sulphonylurea-tolerant crops (e.g. oilseed rape and flax). The *csrl* mutant from *Arabidopsis thaliana* has been used to develop crops insensitive to imidazolinones. More recently it has been discovered that a single mutation (Trp-to-Leu substitution) in plant ALS can cause insensitivity to multiple classes of ALS-inhibiting herbicides in tobacco.

Opportunities for development of crops tolerant to such ALS-inhibiting herbicides are limited, however, by the fact that they have been specifically designed to endow sensitivity to different crops.

Herbicide detoxification

Rapid detoxification of herbicides is a common basis of crop tolerance, enabling their selective use to control weeds without crop damage. Metabolism may occur by a number of mechanisms, involving hydrolysis, oxidation and conjugation to natural products. In transgenic HTCs a single gene is introduced which enables detoxification of the herbicide. Genes which encode for several different herbicide detoxification mechanisms have been transferred to crops using genetic engineering (Table 12.2).

Table 12.2 Herbicide-metabolising enzymes which have been transformed into crop species to produce herbicide-tolerant crops*

Enzyme	Herbicide degraded	Gene source
Glyphosate oxidoreductase	Glyphosate	*Ochrobacterium anthropi* (formerly *Achromobacter* sp.) (*gox*)
Phosphinothricin acetyl transferase	Glufosinate	*Streptomyces viridichromogenes* (*bar*) *Streptomyces hygroscipicus* (*pat*)
Nitralase	Bromoxynil	*Klebsiella ozaenae* (*bxn*)
2,4-D dioxygenase	2,4-D	*Alcaligenes eutrophus* (*tfdA*)
Cytochrome P450 mono-oxygenase	Chlorotoluron atrazine	*Homo sapiens* (*CYP1A1*)
	Chlorotoluron	*Rattus norvegicus* (*CYP1A1*)

* After Devine & Preston (2000).

The metabolic detoxification approach in developing herbicide tolerance is well exemplified in the case of glufosinate (also known as phosphinothricin). Tolerance has been conferred in many crop species, including oilseed rape, cotton, maize and rice.

Glufosinate tolerance

Glufosinate acts as an inhibitor of glutamine synthetase causing disruption of nitrogen metabolism in plants. It is a 'natural product' herbicide, being a breakdown product of bialaphos (phosphinothricinyl-L-alanine-L-alanine) which is an antibiotic tripeptide synthesised by certain species of *Streptomyces*. These microbes are able to inactivate glufosinate by the action of phosphinothricinyl *N*-acetylase (PAT). Glufosinate tolerance in plants (e.g. oilseed rape) was achieved using the genes *bar* and *pat* isolated from two *Streptomyces* species. Trials carried out over several years showed stability of the tolerance and agronomic traits. Generally, the tolerance gene *bar* has been used and microprojectile bombardment of the embryogenic tissues has been used to deliver the plasmid carrying the tolerance gene. Transformations to obtain tolerance in monocot crops such as maize, rice, barley and sugar cane, have involved the use of *Agrobacterium tumefaciens.*

Bromoxynil tolerance

Another example of tolerance resulting from metabolic detoxification is found in bromoxynil-tolerant cotton. This crop is widely grown in the southern cotton-growing areas of the USA. Tobacco and potato also exhibit tolerance.

Bromoxynil is a hydroxybenzonitrile contact herbicide which acts as a photosynthetic electron transport inhibitor and uncoupler. It has been used for the selective control of broad-leaf weeds in cereal crops such as wheat. Normally dicot crops are susceptible to bromoxynil; in transgenic cotton, however, it provides better control of recalcitrant weeds and greater flexibility in time of application.

Bromoxynil tolerance was achieved using a highly resistant field isolate of the soil micro-organism *Klebsiella ozaenae*. This contained a plasmid-borne gene (*oxy*) gene encoding a 38 kDa nitralase which specifically used bromoxynil as a substrate. This enzyme mediates the removal of the cyano group from bromoxynil with the formation of benzoic acid (non-phytotoxic). Tolerant crops can withstand a dose of at least 20 times the recommended application rate of bromoxynil with crop quality remaining unaffected. Tolerance to ioxynil as well as to bromoxynil has been conferred to other crops such as oilseed rape.

Other examples

Other examples of crop tolerance involving metabolic detoxification include degradation of 2,4-D utilising a gene specifying 2,4-D dioxygenase (in cotton) and glutathione transferases (GSTs) (in maize). Tolerance to phenylurea herbicides in soybean has been developed by stimulation of cytochrome P450. Herbicide-metabolising enzymes which have been transformed into crop species to produce HTCs are shown in Table 12.2.

Safeners and antidotes

Herbicide tolerance in crops can be increased by the use of herbicide safeners or antibodies. In cereals several herbicides are marketed in co-formulation with safeners, e.g. the combination of the herbicide fenoxaprop-ethyl with the safener fenchlorazole-ethyl. Increased tolerance results from enhanced detoxification, especially where oxidation or glutathione conjugation reactions are involved. Safeners cause increased glutathione accumulation by enhancing the activity of such enzymes as ATP-sulphurylase, adenosine-5-phosphosulphate sulphotransferase and γ-glutamylcysteine synthetase.

Weed resistance mechanisms

It is relevant to consider the mechanisms involved in the development of weed resistance to herbicides since these can indicate potential approaches in the engineering of crop tolerance. They have been reviewed recently by Devine & Preston (2000) (Table 12.3) and are also considered in Chapter 11.

Table 12.3 Major target sites of herbicide action*

Target site	Mechanism inhibited	Herbicide groups
Q_B PSII protein	Photosynthetic electron transport	Phenylureas, *s*-triazines, uracils
PSI electron acceptor	Photosynthetic electron transport	Bipyridiliums
Phytoene desaturase	Carotenoid biosynthesis	Various 'bleaching' herbicides
Protoporphyrinogen oxidase	Porphyrin biosynthesis	Nitrodiphenyl ethers, oxadiazon
Acetolactate synthase	Branched-chain amino acid biosynthesis	Sulphonylureas, imidazolinones, triazolopyrimidines
Enol-Pyruvyl-shikimate-3-phosphate synthase	Aromatic amino acid biosynthesis	Glyphosate
Glutamine synthetase	Glutamine biosynthesis	Glufosinate
Acetyl-CoA carboxylase	Fatty acid biosynthesis	Cyclohexanediones, aryloxyphenoxypropionates
'Elongase' complex	Fatty acid elongation	Thiocarbamates
α and β-tubulin	Cell division	Dinitroanilines, carbamates, phosphoric amides
Auxin-binding protein	Multiple mechanisms	Phenoxyacetate acids, benzoic acids
Hydroxyphenylpyruvate	Homogentisate biosynthesis	Isoxazoles

* After Devine & Preston (2000).

Resistance based on target site modifications

Target site-based resistance is normally conferred by a mutation in the target protein which decreases herbicide binding without affecting the future of the protein. The major target sites for herbicide action are presented in Table 12.3.

Photosystem II (PS II)

The *s*–triazine, phenylurea and uracil herbicides inhibit photosynthetic electron transport in PS II by binding to the D1 protein and blocking transport of the mobile electron carrier, plastoquinone. In the case of the *s*-triazines, resistance has been reported in over 60 weed species, generally involving a mutation in the *psb*A gene which codes for the D1 protein. In most cases, resistance is due to a Ser_{264}-to-Gly mutation which decreases the binding of *s*-triazines. Alternative mechanisms are involved in the case of other PS II inhibitors.

Photosystem I (PS I) electron acceptors

The bipyridilium herbicides, paraquat and diquat, inhibit photosynthetic electron transport in PS I by diverting electrons from one of the iron–sulphur carriers, possibly ferredoxin. Despite the fact that these herbicides have been used since the 1950s, resistance to paraquat/diquat has been reported in only 25 species. The molecular basis of resistance is uncertain but may involve amplification of the enzymes responsible for the detoxification of oxygen radicals or sequestration of the herbicides away from the chloroplast.

Protoporphyrinogen oxidase (Protox)

This is the final enzyme to operate in the tetrapyrrole biosynthetic pathway prior to branching to form chlorophyll or haem. It is the target site of several groups of bleaching herbicides, including the diphenyl ethers.

Inhibition of Protox leads to the production of large quantities of free protoporhyrin IX in the cytoplasm, resulting in damage in the presence of light and oxygen; resistance to certain Protox inhibitors has been selected for in plant and bacterial cell cultures. No natural resistance has evolved under conventional field application of these herbicides.

ALS

Weed resistance to ALS inhibitors is primarily due to target site mutations and to a lesser degree to enhanced herbicide detoxification. Most mutations occur in five separate conserved domains of the ALS gene. They confer a high level of resistance to sulphonylurea (SU) herbicides, moderate resistance to triazolopyrimidines (TPs) and little or no cross-resistance to imidazolinones (IMs). Mutations at other sites confer different patterns of resistance to the same classes of ALS inhibitors. A Trp_{591}-to-Leu replacement confers high levels of resistance to all classes of ALS inhibitor; the Ser_{670}-to-Asp substitution, however, confers little change in sensitivity to SU and TP herbicides but a high level of resistance to IMs.

5-enol-*Pyruvylshikimate-3 phosphate synthase (EPSPS)*

Glyphosate is a potent inhibitor of EPSPS affecting the biosynthesis of the aromatic amino acids phenylalanine and tyrosine. As previously described, crop tolerance to glyphosate has been introduced by genetic engineering involving CP4 and *gox* genes. Recently glyphosate resistance has been confirmed in two grass species, *Lolium rigidum* and *Eleusine indica*. In the latter, resistance appears to result from a mutation within EPSPS.

Acetyl-CoA carboxylase (ACCase)

The cyclohexanediones (CHD) and aryloxyphenoxypropionates (AOPP) are important graminicides for use in a variety of broadleaf and cereal crops. They act by inhibiting the plastidic form of acetyl-CoA carboxylase (ACCase) in acyl lipid biosynthesis. Plastidic ACCase is different in monocots and dicots; only the latter form is resistant to these herbicides. In certain cereal crops, however, tolerance is due to rapid herbicide detoxification and this mechanism may cause resistance in grass weed species (e.g. *Avena fatua*, *Lolium rigidum*, *Setaria viridis*, *Alopecurus myosuroides*). Resistance may be based on an altered target site or it may be through enhanced metabolic degradation involving, for instance, P450 monooxygenases. Several different mutations can occur, each of which confers a unique pattern of cross-resistance to these herbicides.

α- *and* β-*Tubulin*

α- and β-Tubulin are the building blocks of the tubulin polymers which form the spindle fibres involved in cell division. Tubulin synthesis is blocked by several groups of herbicides, including the dinitroanilines, carbamates and phosphoric amides.

Resistance to these compounds has been recorded in several weed species such as *Eleusine indica* and *Setaria viridis*. In the case of dinitroaniline herbicides it is conferred by Thr_{239} to Ile mutations in an α-tubulin gene.

p-*Hydroxyphenylpyruvate dioxygenase*

p-Hydroxyphenylpyruvate dioxygenase (HPPD) enables the formation of homogenisate from *p*-hydroxyphenylpyruvate and is the precursor of essential components of photosynthesis. HPPD is inhibited by the isoxazoles and whilst field resistance has not been recorded, it has been generated in tobacco by overexpression of an HPPD gene from *Pseudomonas fluorescens*. This approach could be employed to develop crops which are tolerant of HPPD inhibitors.

Resistance based on herbicide metabolism in weeds

The roles of herbicide metabolism in the development of weed resistance, together with the mechanisms involved, have also been reviewed by Devine & Preston (2000). The specific roles of cytochrome P450 enzymes and glutathione transferases have recently been reviewed by Barrett (2000) and Edwards & Dixon (2000) respectively.

Weed species in which enhanced detoxification has been proposed as the resistance mechanism are listed in Table 12.4; it is evident that one or more phases of the metabolism process may be increased.

The role of P450 cytochromes and glutathione S-*transferases*

The resistance attributable to increased P450-based metabolism has been demonstrated for several weed species, including *Lolium rigidum*, *Alopecurus*

Table 12.4 Selected weed species with herbicide-resistant populations attributable to increased herbicide metabolism*

Weed species	Herbicide(s)	Proposed enzyme systems
Alopecurus myosuroides	Chlorotoluron, Pendimethalin, Diclofop-methyl, Fenoxaprop-p-ethyl, Propaquizafop, Chlorsulfuron	Cytochrome P450 mono-oxygenase, Glutathione *S*-transferase
Abutilon theophrasti	Atrazine	Glutathione *S*-transferase
Avena sterilis	Diclofop-methyl	Cytochrome P450 mono-oxygenases
Avena fatua	Triallate	Cytochrome P450?†
Echinochloa idena	Propanil	Amyl acylamidase
Lolium rigidum	Simazine Diclofop-methyl Fluazifop-p-butyl Tralkoxydim Chlorsulfuron Metribuzin Chlorotoluron	Cytochrome P450 mono-oxygenase
Phalaris minor	Isoproturon	Cytochrome P450 mono-oxygenase
Stellaria media	Mecoprop	Cytochrome P450 mono-oxygenase

* After Devine & Preston (2000).

† Resistance due to decreased activation of the herbicide.

myosuroides and *Phalaris minor*. Resistant populations may be cross-resistant and show enhanced metabolism to several classes of herbicides. Multiple detoxification due to different P450 activities appears to be involved, rather than a single P450.

Similarly, the involvement of glutathione *S*-transferases (GSTs) in cross-resistance to multiple classes of herbicides has been reported in various weed species, including blackgrass (*Alopecurus myosuroides*). In England, certain resistant blackgrass populations have differential cross-resistance to the phenylurea, chlorotoluron (PS II inhibitor) and the arylphenoxypropionate, fenoxaprop (ACCase inhibitor). These herbicides have very different modes of action and enhanced rates of detoxification appear to convey cross-resistance. It could be conjectured that resolution of the protein structure for GSTs from crops may enable the discovery of new herbicides specifically designed to be actively detoxified by GSTs in tolerant crops. Maize is an example of a crop in which glutathione conjugation is a major route of herbicide metabolism.

Herbicide-tolerant crops in the USA, Canada and Europe

While the commercial release of transgenic HTCs has yet to be approved in the UK and Europe, their use in Canada and the USA has been widespread for some years. The benefits and lessons from those experiences may be useful in the European context.

Herbicide-tolerant crops in the USA

In the USA the first herbicide-tolerant cultivars to be commercially grown were imidazolinone (IM)-tolerant maize; these had been developed using tissue culture and pollen mutagenesis. Agronomically this development was necessary because although IMs provided selective weed control in soybeans, maize was susceptible to IM soil residues. The introduction of IM-tolerant maize cultivars enabled farmers to continue the traditional maize–soybean crop rotation. Thus, it was possible, using IM-tolerant maize, to control troublesome ACCase-resistant weeds including wild oat (*Avena fatua*), *Lolium multiflorum* and *Setaria viridis* using IM herbicides.

In recent years, the rate of adoption of transgenic crops in the USA has been particularly rapid. This has resulted in the effective displacement of the traditional soybean herbicide market, with reliance on only glyphosate. In 1999, around 50% of the 72 million acres of soybeans sown in the USA were glyphosate-tolerant. Transgenic versions of all major crops were sown in 70 million acres of the USA, and the value is expected to triple by 2004.

Sales of GM herbicide-tolerant seed increased from US $425 million in 1997 to US $1188 million in 1998 and are projected to increase by an average of 210% between 1998 and 2003. It is anticipated that once multiple-trait GM crops become available, expansion of that sector of the agricultural biotechnology market will be even more rapid; increases of 110% per annum between 1998 and 2003 are predicted. Herbicide-tolerant crop technology in four major crops in the USA (corn, cotton, soybean and rice) has been reviewed recently by Baldwin (1999). He has provided an overview of current weed control technology, indicating the gaps, advantages and disadvantages.

In the case of soybean (and cotton), the area of glyphosate-tolerant cultivars accounts for around 50% of the total planted in the USA. This technology has offered improved broad-spectrum weed control and improved control of certain species and larger weeds. The growers have benefited from increased production efficiency and a simplified husbandry regime. Acceptance of the weed control benefits has been rapid, whereas acceptance of the cultivars and certain issues relating to the seed has been slower.

Generally two well-timed glyphosate applications have given excellent overall weed control. However, some shortcomings have been identified, including the following:

- The difficult weed species (e.g. yellow nutsedge, *Cyperus esculentus*) survive if the first application is made too late
- Shade-tolerant weeds (e.g. tall waterhemp, *Amaranthus tuberculatus*) may germinate late, thus escaping the glyphosate treatment
- Glyphosate drift onto susceptible adjacent crops (e.g. conventional corn, rice, cotton) may severely damage or kill these crops in the seedling stage
- Glyphosate may act as a reproductive growth inhibitor, resulting in sterile grain heads and thus reducing yields of susceptible crops
- Farmers may react unfavourably to 'technology fees' placed on seed and to 'grower contracts'

In the case of maize (corn), grower acceptance of herbicide-tolerant cultivars has been slower than for cotton or soybean. Apparently growers do not perceive the herbicide-tolerant corn to have an advantage over traditional programmes. The latter may include an acetamide herbicide (e.g. metolachlor) combined with atrazine, providing an inexpensive, broad-spectrum, soil-applied treatment.

Currently, IM-tolerant corn has been the most widely accepted. However, the same herbicides are used in the soybean rotation crop and the development of ALS-resistant weeds is a major problem. Another difficulty associated with this technology is the fact that some large grain processors do not accept GM maize. Of the herbicide-tolerant crop options available, the greatest potential appears to involve RoundupReady™ maize, owing to the broad spectrum of weed control it provides, the low cost of glyphosate and the greater breadth of crop growth when it may be applied.

In 1999, there were no commercially available herbicide-tolerant cultivars of rice, though development of cultivars tolerant to glufosinate, glyphosate and imazethapyr was underway. These herbicides have shown promise for broad-spectrum weed control and also for control of red rice (*Oryza sativa*). This weed is a major problem in drill-seeded rice in the USA and the use of herbicide-tolerant rice will allow this crop to be grown on land where conventional rice cannot be sown. Concerns that the tolerance gene may spread to red rice by outcrossing is believed to be more perceived than real.

Minimal-tillage systems – seed bank considerations

The use of herbicide-tolerant crops in association with total herbicides might be expected to have an impact on weed population dynamics and, thus, the soil seed banks. The effects of using herbicide-tolerant crops/total herbicide/reduced tillage systems in the USA have been reviewed recently by Forcella (1999). He concluded that consistently excellent weed control was essential to stabilise or reduce weed seed banks; this required that herbicide timing was critical.

This is more easily achieved for weeds which emerge early and rapidly. It is more difficult, however, in the case of weeds which emerge late or protractedly, and it might be anticipated that in such cases increases in seed bank densities will take place under HTC regimes. These problems appear to be less evident under more conventional systems where soil-applied herbicides exert their action over a prolonged period; in comparison the residual effectiveness of total herbicides such as glyphosate is negligible.

The application of such herbicides must be made after critical thresholds have passed. Adequate control of early-emerging species will normally be achieved; weeds with late or extended emergence characteristics (e.g. *Cirsium arvense*) may not be controlled by herbicides with negligible residual properties. The adoption of HTCs will probably result in increased seed banks of such species.

Herbicide-tolerant canola (oilseed rape) in Canada

Herbicide tolerant crops have been tested in Canada for over ten years and have been in farm usage for over five years. The effect of using HTCs on weed population dynamics in Western Canada has been reviewed by Derksen *et al.* (1999) with particular reference to long-term changes resulting from the use of total herbicides in herbicide-tolerant canola (oilseed rape).

While herbicide-tolerant maize and soybeans have been grown in eastern Canada, only herbicide-tolerant canola has been used in western Canada. Cultivars have been developed which are resistant to glyphosate, glufosinate and imidazolinones (IMs). Glyphosate and glufosinate tolerance was achieved using genetic engineering, whereas tolerance to the IMs was by conventional breeding. Around 80% of the 5.6 million hectares grown in 1999 were herbicide-tolerant. Their introduction has provided farmers with the opportunity to control previously unmanageable weeds in Canada. Thus, canola has become the 'clean-up' crop of choice for weedy fields.

This has intensified the selection pressure due to use of glyphosate, glufosinate and imazethapyr. In particular, the adoption of reduced-tillage systems has enabled the use of glyphosate-tolerant canola in arid areas of the prairies. If such systems are used excessively, adverse changes in weed dynamics may occur, resulting in changes in weed communities. Adverse changes in the weed community are reduced, however, by use of an integrated weed management programme involving the three herbicide/cultivar systems. Problems which have been identified include the following:

- The occurrence of volunteer herbicide-tolerant canola; canola seeds are subject to dormancy and can cause a weed problem after several years of canola growth
- This problem may be particularly evident where glyphosate-tolerant canola is grown in reduced tillage systems
- Control of such volunteer canola in field margins will require a change of herbicide
- Volunteers can cause problems for growers of organic crops and of Identity

Preserved (IP) canola varieties; this is particularly so if the crop is destined for GMO-free countries (GMO, genetically modified organism)

On the positive side, the availability of herbicide-tolerant canola has provided the Canadian farmer with novel options for weed control. These include:

- Reduced reliance on soil-applied residual herbicides (e.g. trifluralin for broadleaf weed control)
- Reduced reliance on selective post-emergence graminicides
- The ability to control resistant grass weeds (e.g. *Avena fatua*)
- Exploitation of zero and minimum tillage systems; under prairie conditions soil erosion and soil moisture losses are minimised, thus maximising crop yields

Europe

Many growers in Europe would appreciate the opportunity to embrace these revolutionary new technologies. There have been delays, however, in the revision of the legislation relating to the use of GMOs (Directive: 90/219/EEC) and their deliberate release into the environment (Directive: 90/220/EEC).

Environmental issues

In Canada and the USA, the use of GM technology to protect crops from insects and diseases, as well as herbicides, is regarded as a means of increasing crop productivity in an environmentally sensitive manner. In Europe, however, there are major concerns relating to the perceived risks associated with the development of GM crops. These concerns include:

- The risks of transfer of antibiotic resistance to the human food chain
- Labelling of products containing ingredients from GM crops
- Interspecies transfer of resistance genes to related species
- Threats to biodiversity

In the UK the two major areas of environmental concern relate to the occurrence of volunteers from GM crops, and the possibility of gene introgression. In particular it is perceived that problems may be caused by the existence of volunteer potatoes and the establishment of feral populations of rapeseed. Where these volunteers are herbicide-tolerant, their control may cause problems.

Gene introgression – risk categories

Gene introgression may result from inter- or intra-specific hybridisation between crops and weed plants. As a result, herbicide tolerance may become expressed in agricultural or adjacent ecosystems. The probability of gene flow from a crop to related wild species has been assessed in the UK and three categories of risk can be defined ('minimal', 'low probability' and 'high probability'). The crops identified in these categories are as follows:

- Minimal risk – potato, tomato, wheat, maize, grain legumes
- Low probability – rapeseed (*Brassica napus*), flax, barley, raspberry
- High probability – sugarbeet, forage grasses

Particular interest is applied to rapeseed, which is likely to be the first to be grown as herbicidal-tolerant cultivars. Work carried out in Denmark has shown that *Brassica campestris*-like plants with 20 chromosomes, a high pollen fertility and carrying a transgene from rapeseed can be produced as early as the first back-cross generation; interspecific back-crossing was evident under field conditions. The existence of fertile transgenic weed-like plants after two generations of hybridisation and back-crossing suggests that rapid spread of genes from rapeseed to the weedy relative *Brassica campestris* may occur.

In the case of sugarbeet, introgression of tolerance genes may occur to related species such as fat-hen (*Chenopodium album*). No generalisation can be made, however, since genes which modify reproductive behaviour could alter the crop category and, thus, the environmental impact. Further, the probability of gene flow from crops to weedy relatives may be influenced by geographical location.

At present, it is difficult to forecast the existence and importance of transgene movement for several reasons, including the variability and difficulty in interpreting the limited current research. In addition, the results of small-plot studies may not be extrapolated readily to the field scale and also there is uncertainty as to whether herbicide tolerance genes will influence the ecological behaviour of the crop, its volunteers or wild relatives. The current range of field trials being carried out at certain sites throughout the UK should help to clarify these environmental issues.

Effects on weed evolution

It is believed that the commercialisation of crops containing transgenes for stress tolerance will inevitably lead to the general dispersal of these genes via crop–wild relative hybrids or crop escapes. It is unlikely that the escape of stress tolerance genes will result in the production of new pernicious weeds, but genotypes that out-compete less competitive conspecifics may be formed.

In arable crop rotations there is an ever-increasing dependence on herbicides. Inevitably this has resulted in the selection of plant biotypes with resistance to more than one herbicide class. The rate of this process is being accelerated because a number of crops are being tailored to specific niches. This is exemplified in the following cases:

- In Australia, herbicide-tolerant GM lupins allow the use of non-selective herbicides in herbicide-resistant grass communities

- In the USA, GM upland cotton (*Gossypium hirsutum*) is used in rotations with maize and/or soybean
- In Canada, GM herbicide-tolerant oilseed rape and flax (*Linum usitatissimum*) have niches in prairie rotations with cereals

Herbicide-tolerant plants may have potentially undesirable effects on non-agricultural habitats. In Western Australia, plants of simazine-resistant blue lupins (*Lupinus angustifolius*) are well established along roadsides and in disturbed riverine habitats. Phosphinothricin is used to control these ruderals but this will not be possible if the transgene for phosphinothricin tolerance (*bar*), currently in GM sweet lupin cultivars, spreads to the feral *Lupinus angustifolius* by hybridisation.

Gene flow

The possibility of gene flow from transgenic crops to related plant species is influenced by the distance of pollination and sexual compatibility.

Studies with potato and oilseed rape indicate that cross-pollination will be nil or negligible respectively at a distance of 48 m from the crop. There was no evidence of sexual compatibility between potato and *Solanum nigrum* or *Solanum dulcamara*. However, oilseed rape can cross-pollinate with *Brassica rapa*, *Brassica adpressa*, *Brassica juncea* and *Raphanus raphanistrum*; cross-pollination with *Sinapsis arvensis*, however, was rare. Experience with oilseed rape (canola) shows that, in practice, cross-pollination is negligible provided that isolation occurs. The MAFF (now DEFRA) requirement of 50 m between low- and high-erucic rapeseeds has proven totally successful in practice. Cross-pollination in commercial maize seems possible but in practice volunteers do not normally occur, and commercial crops are not home-saved for seed. Some unresolved challenges on gene dispersal are possible in relation to sugar beet and rye-grasses.

The presence of multiple transgenes in a crop, feral or weed species, arising from cross-pollination with transgenic crops, potentially may lead to instability in transgene expression. Instability generally means that transgene expression will be switched down or switched off. As a result these plants revert to their wild-type phenotype; in practice herbicide-tolerant plants could become susceptible to the specific herbicide. In natural habitats such transgene instability would be expected to have a negligible impact on plants.

Weed population dynamics

Predictive modelling

The availability of transgenic HTCs which enable the use of broad-spectrum herbicides such as glyphosate and glufosinate will have implications for farming systems. It is reasonable to assume that weed population shifts may occur and that weed resistance may develop. Evaluation of the impact of HTCs on weed populations requires an insight into weed behaviour, population dynamics, effects on agroecosystems and the efficacy of weed control technologies.

Modelling approaches can be used to evaluate the long-term impact on weed population dynamics of introducing transgenic crops in combination with broad-spectrum herbicides. The possible risks of introducing such technology include the development of weed resistance through the intensive use of single herbicides, change in species composition of the weed flora/seed bank and the effect of herbicide-tolerant volunteers on successive crops.

Models for population dynamics combined with population genetic models could assist in the risk evaluation under different scenarios.

The importance of mathematical modelling as a means of predicting weed population changes and developing weed control strategies has been stressed. Models of weed infestation, population growth and control have been invaluable for organising biological information on weeds and for developing control strategies. Their value extends beyond being research tools since they may serve as experimental ‘test beds’. Integrated weed management requires a thorough understanding of the population dynamics of weed communities and their constituent species populations. In particular it requires appreciation of the factors which determine the rates of spread of weed species, the rates at which increase occurs when they reach a specific location and the mechanisms by which spatial spread and abundance of weeds can be minimised/reduced.

Models which may have relevance in predicting the effect of herbicide-tolerant crops/total weedkillers on weed population dynamics should include consideration of prediction of weed invasion, seed disposal, weed population density, weed control decision thresholds/timing of control and weed resistance to herbicides.

The use of weed population models in evaluation/management of cropping systems requires improvements in three key areas:

- The incorporation of weed–crop interaction
- The degree of detail in the description of crop management
- The recognition of spatial heterogeneity of the weed population

Ecophysical models

Currently the most complete description of such interactions is provided by the ‘ecophysical’ models (e.g. Lindquist & Kropff, 1996). These models simulate annual competition for light, water and nutrients between a crop and one or more weeds. Despite their limitations they are suitable for examining crop management effects (such as sowing date, crop density, nitrogen fertilisation and weeding) on weed biomass and seed production. There is a view that, rather than integrating the ecophysiological models directly into weed population models, the former are used to generate parameter values for the latter. These could include seed mortality, seedling survival, and weed fecundity under different crops, soil conditions and climatic years.

Simulations have been used to model the ‘selection pressure’ exerted by herbicides and the evolution of herbicide resistance. Herbicide-resistant genes are introduced into the population both by immigration of pollen and seed and by 'genetic drift' within the existing populations. Management of resistance may involve the use of alternative herbicides to remove 'resistant' plants and/or the manipulation of the non-resistant gene type to increase its incidence in the population. Modelling has indicated that the latter may be more cost-effective.

Weed management models have addressed three questions. First, what relationship exists between the level of weed infestation and the crop losses? Secondly, what level of control measure is required to contain the infestation or total eradication of the weed? Thirdly, what level of weed infestation is required to justify control measures?

Sustainable systems of weed management would require consideration of more fundamental questions. For example, how can the environmental impacts of herbicides be reduced through the use of biological/physical control measures? How can the more selective use of herbicides be promoted while being compatible with economically acceptable levels of weed control? How can the economic risks of switching to non-chemical control strategies be minimised?

Such considerations become ever more imperative, with or without the adoption of HTCs in association with non-selective herbicides.

Oilseed rape – herbicide tolerance and its implications

Conferring technology

The advances in oilseed rape, reviewed by Werner (1993), are highlighted here since it is likely that this will be the first transgenic crop released for commercial use. Varietal development is influenced not only by traditional breeding objectives but by techniques available to the breeder (Fig. 12.2). Breeding technology thus complements conventional breeding approaches which are based on the essential components of crossing and selection. Improved technology can assist the breeder in four major areas by:

- Expanding the sources of genetic variation
- Improving the analytical tools by which selection is aided
- The use of tissue culture to accelerate breeding programmes
- The development of alternative seed production strategies

The analytical tools include marker techniques such as restriction fragment length polymorphisms (RFLPs) used to create gene maps, random amplified polymorphic DNAs (RAPDs), amplified fragment length polymorphism (AFLP) and the green fluorescent protein (GFP) marker gene. DNA markers have been developed to the stage where they can be used to test alternative selection methods, thus reducing the need to measure phenotypes directly.

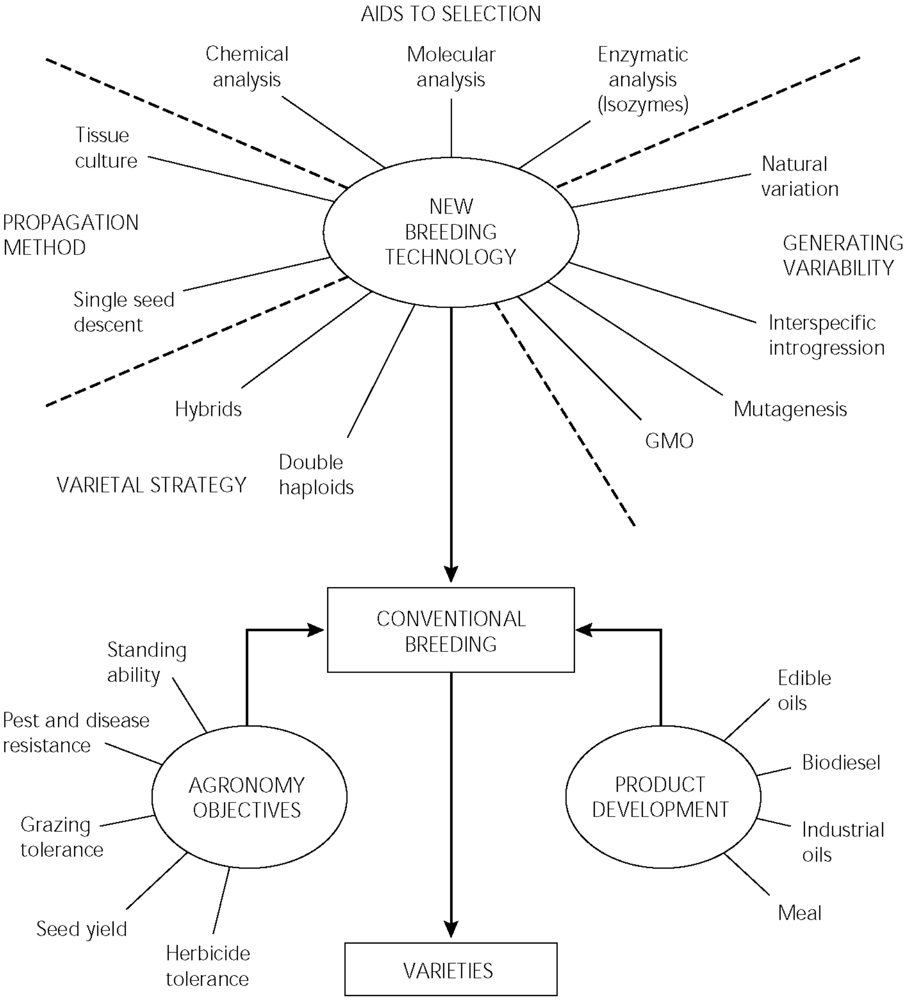

Fig. 12.2 Techniques available in the development of new cultivars. (*After Werner, 1993*).

Phenotypic measurement (e.g. of glucosinolate content) can be replaced with evaluation of marker genotypes known to be linked to the gene(s) responsible for the selection trait. However, the use of markers requires reliable correlations between marker genotypes and the desired phenotype and also the development of faster, cheaper DNA techniques which enable screening of large numbers of individuals (e.g. conversion of RFLP to a polymerase chain reaction (PCR) primer).

Tissue culture technology is well established but the regeneration of transformed tissue may be a problem.

UK trials with GM herbicide-tolerant oilseed rape

It is evident from the foregoing that the cultivation of HTCs in the UK will result in changes in herbicide usage from the current use of selective herbicides to that of the broad-spectrum chemicals which the transgenic varieties tolerate. The volunteers subsequently generated by these crops may require different herbicides to eliminate them. Such changes in herbicide treatment programmes may have effects on the biodiversity of fields and field margins.

Hybridisation and volunteers

Trials conducted in the UK by the National Institute of Agricultural Botany (NIAB), Cambridge, have compared the impacts on field margins of glyphosate, glufosinate and currently used herbicides. Herbicide-treated field margins have also been monitored to determine whether feral populations of herbicide-tolerant oilseed rape (OSR) are likely to establish adjacent to crops of GM OSR. At each trial site, pollination of the nearest OSR crop (0.5–1 km), OSR volunteers and related cruciferous weeds/hedgerow plants were monitored within 200 m of the site. Seed samples were collected from plants which flowered synchronously with the GM OSR and tested for the presence of the herbicide tolerance gene (*bar*) using PCR. GM seed dispersal and seed bank monitoring were also carried out at each site.

These studies were limited in scale, but appeared to indicate that cross-pollination with other OSR crops or with volunteer or feral rape did not occur. The *bar* gene was not detected in the seed of cruciferous weeds growing in the field margins adjacent to the GM crops. Weediness and invasiveness of volunteer populations of GM OSR were increased in crops following the OSR crops (e.g. sugar beet and wheat). The occurrence of herbicide-tolerant volunteers was low (e.g. 6.5% of total volunteers), very low or absent, their presence being associated with seed spillage and unsprayed areas.

The extent of cross-pollination from plants containing marker transgenes to plants of the same crop or related species has been studied in OSR (and other crops) by the Agriculture and Food Research Council (AFRC) Institute of Plant Science Research, John Innes Centre ('Prosamo' project), Norwich. Seeds were harvested from non-transgenic plants at distance of 1–47 m and at 70 m from the transgenic crop area. Plants grown from these seeds were screened to confirm that they were heterozygous for the herbicide-resistance transgene; they were also monitored for occurrence of the *bar* gene.

Pollination frequency fell sharply up to 12 m and was negligible at 47 m. The honey bee appeared to be the principal pollinating insect and the patterns of pollination were influenced by the position of the hives. The provision of a buffer strip of non-transgenic OSR surrounding the plot of transgenic plants may reduce the possibility of transgenic pollen being taken by bees from distant hives.

The FACTT programme

The FACTT (Familiarisation and Acceptance of Crops incorporating Transgenic Technology) programme is a four-year project partly funded by the EU. It has enabled the introduction of many desired traits into plant breeding programmes. The project involved 21 partners from six EU member states, encompassing the main OSR-growing areas in the EU.

The results indicate that there was little difference between the transgenic and conventional varieties in respect to plant vigour and maturity; they differed only in the modified trait. Generally, the application of glufosinate-ammonium was most effective, resulting in a mean yield increase at most sites. It also offered the possibilities of controlling *Brassica* weeds within the OSR crops, and rotational control of herbicide-resistant grass weeds.

In conclusion, herbicide tolerant OSR appears to offer the potential of a useful alternative weed control strategy for the grower. Provisos, however, include the following:

- Control of HT volunteers in following crops must be carried out using another herbicide
- Isolation distances between HT and conventional crops should be used to minimise cross-pollination
- Distances similar to those used for high-erucic-acid rapeseed are recommended

Rules on releases of GMOs in the UK

The regulations relating to the release of GMOs in the UK have been reviewed by Marquard & Steele (1993) and Glover (1994). They changed in 1993 when the Genetically Modified Organisms (Deliberate Release) Regulations 1992 became effective. The regulations addressed issues which arose from the proposed experimental or commercial release of GMOs into the environment. In particular they related to the possible persistence or spread to other organisms (including humans) of 'artificially generated heritable properties'. While attempting to ensure that safety questions are adequately addressed, one must balance the risks associated with release against the potential benefits of new technology.

All proposals relating to release or marketing of GMOs are subject to the requirements of Part VI of the Environmental Protection Act (EPA) 1990 and the GMO (Deliberate Release) Regulations 1992. In the UK these regulations implement the EC Directive 90/200/EEC on the deliberate release of GMOs into the environment; other member countries are required to effect their own national legislation.

In this context, the term 'GMO' relates to organisms derived from the use of certain 'artificial techniques of genetic modification' which are prescribed in the 1991 Regulations. Techniques would include:

- Insertion into an organism of nucleic acid which has been prepared outside that organism
- Fusion of two or more cells to form cells with novel combinations of genetic materials
- The use of recombinant DNA molecules in in-vitro fertilisation, conjugation, transduction, transformation and induction of polyploidy

The release consent process

Normally the release or marketing of such GMOs requires the consent of the Secretary of State (SOS) for the Environment. Where appropriate the SOS may act jointly with the authority in England or the respective SOS for Scotland or Wales. Although the decision rests with the SOS, in practice authority is delegated to appropriate officials. Where human health and safety are additional to environmental considerations, any proposal by the SOS to grant consent must be first agreed with the Health and Safety Executive (HSE); see also Chapter 7, 'FEPA and COPR'. The main stages involved in processing applications to release GMOs in the UK are summarised in Fig. 12.3.

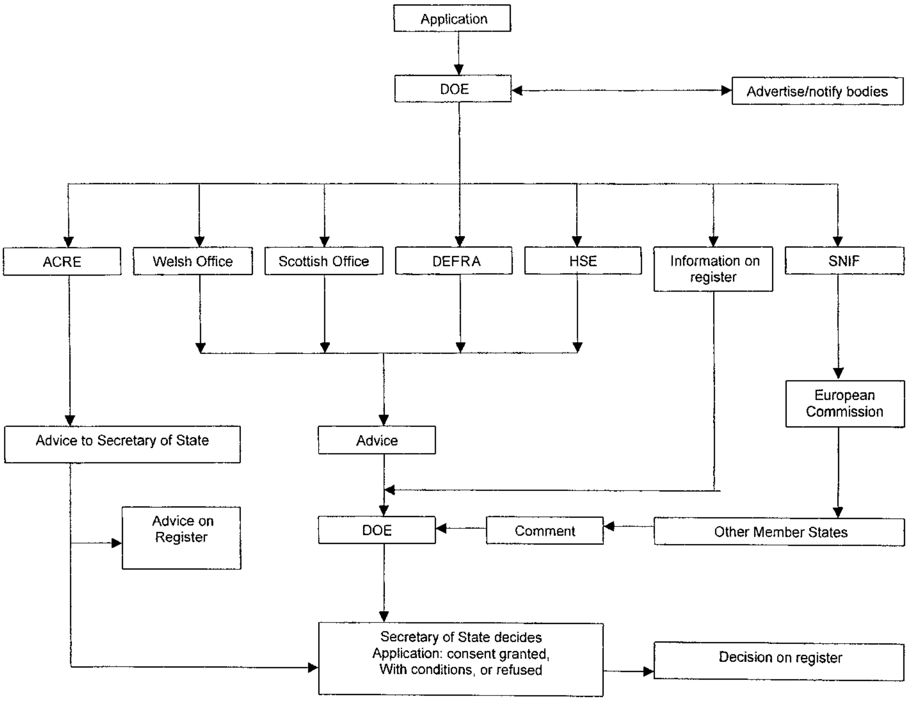

Fig. 12.3 Main stages for processing applications to release GMOs in Great Britain. (*Anon, 1997.*)

These arrangements may appear to be cumbersome but, in practice, the HSE and the other Government Departments have agreed that the DEFRA (Biotechnology Unit) should coordinate consideration of all release consent applications. It also acts as the channel of communication with the EU and the secretariat for the Advisory Committee on Releases to the Environment (ACRE). ACRE was set up to advise the SOSs. It comprises scientific experts and representatives of various interests, including industry and environmental groups. ACRE is intended to advise specifically on whether an application to release or market GMOs should be granted.

On receipt of a release or marketing application, DEFRA circulates it to the HSE and other relevant Government Departments. Following a preliminary review, it is circulated to ACRE for advice. A decision letter which takes account of all relevant views is subsequently issued by DEFRA on behalf of the SOS. It may give consent with enforceable conditions attached which encompass protection of the environment and human health. The intention is to ensure that any risks associated with the release will be prevented or minimised.

Consent to market GMOs

The review process relating to market consent applications is similar to those for release consent. If the review outcome is favourable, the product dossier is sent to the Commission of the EU for clearance by other member states. When approved, the product may be marketed in any community state, subject to the proviso that it satisfies the non-GMO requirements of any relevant product legislation. The use of pesticides is regulated independently of the introductions of plant varieties. In the UK this is enabled by the Pesticides Safety Directorate (Control of Pesticides Regulations 1986; Plant Protection Products Regulations 1995) and the Plant Variety Rights Office (Council Directive 40/457/EEC on Common Catalogue of Varieties of Agricultural Plant Species and 70/458/EEC on Vegetable Seed).

Enforcement of the GMO consent system remains with the SOS, who appoints inspectors with appropriate rights to enforce the legal requirements. In practice, the SOS has an agreement with the Health and Safety Commission, which has directed HSE inspectors to perform the delegated enforcement functions.

The regulatory policy on GMO releases is intended to impose the least burden on industry consistent with adequate risk-based environmental and human health protection. Whilst protecting their patent rights, the applicant must ensure that the information provided is sufficiently detailed and comprehensible to make clear the intentions and risk evaluations. Consistently with adequate safety provision the policy is intended to encourage the development of products which offer positive environmental benefits such as reducing the use of harmful chemicals by the use of GMOs.

In regulatory decision-making the issue of impact of gene flow is an important area. Registration of herbicide-tolerant transgenic varieties usually requires that the company describes the strategies required for the control of weeds and volunteer plants which may be resistant to a specific herbicide. This may be of particular importance where a company introduces more than one herbicide tolerance transgene into a crop variety.

In future, regulatory approval may be dependent on the provision of comprehensive monitoring and reporting back to the regulatory authorities. Companies will be required to outline their strategies for handling multiple herbicide tolerance in breeding, or through gene flow to other species.

Farm practice

If the identity and integrity of specific GM crops should be maintained, then investment will be required in the provision of extra storage facilities, both on farms and with downstream users. In field husbandry, GM releases would require greater control of volunteers where they are regarded as a problem. For example, increased segregation of oilseeds, pulses and cereals would be needed.

The introduction of GM plants to agriculture offers great potential both for food and non-food crops. Within the farming industry, however, practices will require to be adapted to avoid problems, most of which have been identified. Some issues remain unresolved, however, especially at business and international levels.

The agricultural industry has developed strategies for the use of herbicide-tolerant transgenic varieties. In UK, Codes of Practice (British Society of Plant Breeders, National Farmers' Union, UK Agricultural Supply Trade Association), LEAF (Linking Environment and Farming) Guidelines for Integrated Crop Management and the Pesticides Forum may provide useful means of facilitating the use of transgenic crops in the future.

Conclusions

(1) These developments in plant genomics, molecular biology and genetic transformation enable biology to rival chemistry as a source of future innovation in herbicide discovery and application.
(2) The advantages resulting from the use of HTC include improved yield, quality and unit cost of production; in more arid conditions HTCs may be used in low-tillage systems.
(3) The disadvantages include the danger of cross-pollination of genes endowing tolerance, and the development of herbicide-tolerant volunteers and herbicide-resistant weeds.
(4) Herbicide tolerance can be conferred by mechanisms including target site manipulation or metabolic detoxification of the herbicide.
(5) The engineering of tolerance to glyphosate into crops such as soybean, cotton and maize has perhaps been the most notable achievement of plant biotechnology. In soybean, tolerance is due to modification of the EPSPS target site combined with enhanced detoxification of glyphosate.

(6) The use of safeners or antibodies can increase herbicide tolerance in crops: these act by enhancing the rate of herbicide detoxification, especially where oxidation or glutathione conjugation reactions are involved.

(7) Similar mechanisms of resistance have developed naturally in weeds based on target site modifications or enhanced metabolic detoxification of the active ingredient. Enhanced rates of detoxification appear to convey cross-resistance; resolution of the protein structures for GSTs from crops may enable the discovery of new herbicides designed to be selectively detoxified by GSTs in tolerant crops.

(8) HTCs, notably soybean, cotton and corn, have been successfully grown in the USA and Canada. Their use in association with reduced-tillage systems required consistently excellent weed control to reduce or stabilise weed seed banks; herbicide timing was critical.

(9) Growth of HT canola in Canada for some years has identified a number of possible problems including the occurrence of volunteer HT canola, particularly in reduced-tillage systems; these may cause problems for growers of organic crops or Identity Preserved (IP) canola varieties.

(10) The availability of HT canola has provided the Canadian farmer with a 'clean-up' crop for weedy fields, thus reducing reliance on soil-applied residual herbicides and selective post-emergence graminicides. This has enabled control of resistant grass weeds and enabled exploitation of zero and minimum-tillage systems, thus minimising soil erosion and soil moisture losses.

(11) The environmental risks associated with HTCs have been examined in UK field trials, especially with oilseed rape. It is difficult to forecast the importance of transgene movement but current trials should help to resolve this uncertainty.

(12) The use of broad-spectrum total herbicides such as glyphosate or glufosinate will have implications for farming systems. Weed population shifts may occur and weed resistance may develop. Modelling approaches can be used to predict long-term impacts of HTC/broad-spectrum herbicides on weed population dynamics.

(13) Regulatory policies on GMO releases have been developed and are intended to impose the least burden on industry consistent with adequate risk-based environmental and human health protection.

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Chapter 13
Non-chemical Weed Management

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Introduction

From the 18th century until the introduction of herbicides, weed management on agricultural land depended largely on crop rotation, soil cultivation and seed cleaning to keep weeds at a manageable level. Growing a succession of different crops prevented any single weed species from becoming dominant. In addition, 'cleaning crops' were included to reduce the potential weed population before growing poorly competitive crops known to favour weeds. Soil cultivation was employed to bury weeds after harvest and to provide a clean seedbed for drilling the following crop. A measure of additional weed management was obtained by prolonging the period of seedbed preparation, and timing cultivations to kill germinating weeds. Direct weed management methods in the crop were limited to post-emergence harrowing in tolerant crops, mechanical inter-row cultivations and hand hoeing. It was the introduction of improved seed-cleaning machinery that probably made the greatest single contribution to reducing weed problems before the advent of herbicides.

The conversion to organic and low-input farming systems has brought about a re-evaluation of non-chemical weed management strategies that involve the whole cropping system. Cultural factors again provide an element of residual weed management, although their contribution has been modified by developments in production methods, in market requirements and in the range of crops grown. The main change that has taken place, however, has been an increase in the range and sophistication of direct weeding equipment now available and under development to deal with weeds. This chapter outlines the cultural and direct methods for managing weeds on agricultural land without the use of herbicides. Non-chemical weed management is also applicable to other situations where the use of herbicides may be unacceptable, such as in amenity areas.

Cultural weed management

Crop rotation

The unstable environment created by variation of the cropping sequence helps to prevent the annual recurrence of conditions that favour a particular weed. Whilst the introduction of unfavourable conditions and practices into a rotation may not eliminate a troublesome weed species completely, it can limit the opportunities for growth and reproduction. Weed problems in a poorly competitive crop may be reduced by growing a highly competitive crop before it in the rotation. A 'cleaning' crop like potato in the rotation will also lessen weed numbers in a subsequent crop, provided that potato tubers are not left in the soil after harvest to cause a volunteer weed problem. However, maintaining a particular rotation solely for suppressing weeds may be difficult to justify. Even in organic systems, other factors, including pest and disease avoidance, the need to balance soil fertility levels, and economic considerations, also determine the cropping sequence. Nevertheless a competitive grass/clover ley mixture, sown primarily to improve soil fertility, will also help to reduce the weed seed bank through seed deaths that occur during the ley period as well as suppressing further weed seed production. In perennial crops and permanent grassland, there is no opportunity for rotation after crop establishment. Land preparation is therefore vital to avoid or minimise perennial weed problems at the outset. On some soils, improved drainage may help to eliminate weeds that favour wet conditions.

On light to medium soils a well-designed rotation should avoid the need for unprofitable fallow periods to reduce perennial weeds. The economics of taking land out of production for a growing season, together with undesirable effects on the soil and the environment through a lack of vegetation cover, make the use of a full fallow unacceptable for weed management in organic and low-input systems. Fallowing the land for part of the growing season, as a bastard fallow, may be just as effective and can be fitted into most rotations. If dry conditions prevail during the bastard fallow, regular cultivation with spring tines will bring the rhizomes of grass weeds to the soil surface, where they desiccate and die. This technique is often used after a ley to reduce perennial weeds before sowing a winter cereal. The inclusion of short-term or rapidly maturing crops that require only a relatively brief interval between crop establishment and harvest may provide the same effect as a part fallow. Both encourage weed emergence but do not allow time for the weeds to set seed or increase vegetatively between cultivations.

Intercropping offers scope for increasing the level of weed suppression within a single crop. However, improved weed management alone is unlikely to merit the insertion of a second crop and there must be additional advantages; increased yield and reduced pest problems are probably the main benefits expected. Intercropping can have an important role in any sustainable or integrated crop management system but may be of particular significance in less-developed countries.

The inclusion of a cover-crop extends the opportunity for providing variation within the rotation at a time when the land might otherwise lie uncropped. The choice of cover-crop depends on its purpose but it is important that a cover-crop does not provide a 'green bridge' for pests and diseases. Rapid early development and the formation of a dense leaf canopy are the attributes needed for weed suppression. Reduced light transmittance and differences in soil temperature and moisture beneath the cover-crop have an important effect on weed development. In addition, the cover-crop provides a protective habitat for seed predators that may help to reduce weed-seed numbers in the soil. Cover-crops are often sown in the autumn and killed before a following crop is planted in spring. As the residues left on the soil surface decompose they may produce natural phytotoxins that continue to inhibit the germination and development of weeds in close proximity. These allelochemicals may also affect the germination of field-sown small-seeded crops. Incorporation of the residues can dilute the allelopathic effect.

Choice of cultivar

Selective breeding has resulted in a range of cultivars of most crops, with specific attributes to meet particular requirements. Selection for attributes that improve weed suppression is difficult because the traits associated with competitive ability against weeds can change with the development stage of the crop. There is also a difference between cultivars that tolerate weeds and those that actively suppress them. Unfortunately, there is limited information available which compares the competitive abilities of different cultivars against weeds.

Restriction of light through shading by the crop canopy is one way to manipulate the weed population through cultivar choice. The traditional long-strawed cereal cultivars are known to reduce weed numbers and biomass more than modern short-strawed varieties. However, plant breeders are unlikely to select for attributes such as tallness that might increase the risk of lodging. There are many other attributes, including differential rooting patterns, early vigour, leaf size and allelopathic potential, that would confer greater competitive ability. Even selection for a simple character such as large seed size can significantly improve early crop establishment, which is vital for weed suppression.

Crop establishment

In all crops, the use of high-quality seed will ensure rapid and even germination, and improve crop uniformity after emergence. Plants that emerge first in the field are known to have a competitive advantage over those that emerge later. For the crop, emerging first also confers greater selectivity between crop and weeds during subsequent weeding operations. The choice of plant-raising system can provide the crop with that early advantage over the weeds. The use of primed or pre-germinated seed, for example, and the transplanting of bare-rooted or module-raised seedlings can put the crop ahead of the weeds.

Plant spacing

In cereals, increasing plant density through both increased seed rate and narrower row spacing can be effective in suppressing weeds and hence in minimising weed management inputs. Sowing cereals at narrow row spacings will also reduce weed development by increasing the rate of canopy closure. However, increased seed rate alone has been shown to provide greater weed suppression than a narrower row spacing.

Whilst there may be opportunities to adjust plant spacing for greater weed suppression in some crops, this is not so for all. In field vegetables, there may be limitations due to the requirement for a crop to be grown to particular market specifications, or to allow access for mechanical weeding. The restricted soil fertility in organic systems may also determine optimum plant density. Even with cereals, there are some concerns regarding the negative effects that increased seed rate may have on subsequent grain quality.

Limiting the introduction of weeds

Many mechanisms, including animals, wind, fibres and farm machinery, offer a means of introducing weed propagules and potential new weed species to a field. Weed seeds may even be dispersed in irrigation water taken from open waterways. Contaminated crop seed used to be a major source of new weed seeds and it continues to be an important agency for the spread of some weed species. Weeds sown with the crop will emerge in the crop row, where they are most difficult to remove. Crop seed produced outside the UK, provides a route for the introduction of alien species and of common weeds from a different genetic background. Alien weeds that are within the limits of their geographical range may germinate, grow and multiply to become a future weed problem. Repeated introduction can also ensure the survival of species that are at their geographical limit. Seed crops that are grown organically may have greater potential for weed seed contamination than their conventionally grown counterparts if weed management in the parent crop is poor. There are obvious attractions for organic and conventional growers in using home-saved seed, including cost savings, availability and adaptation to local conditions, but weed seed contamination is often greater in home-saved than in merchant's seed.

The use of soil improvers, manures and mulches is another potential source of weed seed contamination. Composted green waste is used to improve soil quality, or as mulch, and other compost mixtures are used in the production of transplants. If the composting process is carried out correctly, no viable weed seeds should remain. However, wind-blown seeds may contaminate compost and other soil amendments stored in the open before use. Harvested crop materials that have not been composted, such as cereal straw mulches, present an even greater risk for introducing weed and volunteer crop seeds.

Crop harvest is the crucial time for prevention of the dispersal of both crop and weed propagules. Weeds that mature at the time of cereal harvest will have a proportion of their seeds re-introduced into the field. Other weed seeds and some cereal grains may remain lodged on the combine to be deposited at a later time and possibly at a great distance from the original field. Crop propagules missed during the harvesting process, for example seeds of oilseed rape and tubers and seeds of potato, can cause severe volunteer weed problems in following crops. Prevention of the re-introduction and spread of weeds at harvest is an important opportunity for limiting future weed populations.

Field margins have been considered a likely source of weeds that will spread into the crop, but most of the species in the margins do not occur in the crop area. However, some pernicious weeds like creeping thistle (*Cirsium arvense*), couch grass (*Elytrigia repens*) and cleavers (*Galium aparine*) pose a real threat. The rate of spread of these aggressive weeds can be reduced but not prevented by sowing grass and wildflower boundary strips.

Cultivation

Cultivations are often classed as primary, secondary and tertiary tillage. For primary tillage, there has been much discussion on the relative merits of ploughing compared with reduced-tillage systems for weed management. With reduced-cultivation systems there is less risk of soil erosion and greater conservation of soil moisture. The plough deals with the potential annual weed population by moving recently shed seeds below the depth from which they will germinate. This can lead to long-term problems because the seeds may persist in the soil seed bank until returned to the soil surface by subsequent cultivations. Under a reduced-tillage system, shallow cultivations maintain the fresh weed seeds near the soil surface to germinate and be killed by further cultivations. Annual broad-leaved weed populations may decline but perennial and grass weeds often increase in density with reduced tillage. In organic farming systems, perennial weeds are known to increase and, depending on the weeds involved, it may be necessary to plough periodically to keep them at a manageable level.

Secondary tillage is used to prepare the seedbed prior to crop establishment but the choice of seedbed that is best for weed management is not clear-cut. A fine, level seedbed makes drilling and subsequent weeding operations easier but encourages greater weed emergence. A lumpy seedbed generally produces fewer weed seedlings but the clods of soil give the seedlings greater protection against weeding implements. The timing of seedbed preparations also affects weed populations. Problematic weed species that emerge only at particular times of year may be avoided by adjusting the timing of seedbed operations and the interval before crop sowing to prevent crop and weed emergence coinciding. Traditionally, winter wheat was sown as late as possible to allow blackgrass (*Alopecurus myosuroides*) to germinate and be managed before the cereal crop was established. Currently, the aim is to drill autumn cereals as early as possible and use herbicides to manage the blackgrass.

The stale or false seedbed technique is based on the principle of ‘flushing out’ germinable weed seeds before cropping. Soil cultivation takes place days, weeks or even months before sowing or transplanting a crop, to allow the main flush of weed seedlings to emerge. The seedlings are killed by flaming or light cultivation shortly before cropping but it is important not to cultivate below the top 1–2 cm of soil, otherwise further weeds may emerge. The stale seedbed depletes the seed bank in the surface layer of soil and reduces subsequent weed emergence in the established crop. A similar effect may be achieved by preparing the seedbed early and delaying crop drilling for a few days. This allows the weeds more time to emerge before flame weeding or blind harrowing kills them prior to crop emergence.

Meeting the germination requirements of the different weed species is important for improving the efficacy of the stale seedbed and other delayed-drilling techniques. Dry soil conditions will make seed germination erratic and delay weed emergence. There is the potential to enhance weed seed germination by laying a short-term pre-planting mulch of black polyethylene sheeting over the cultivated soil for four to six weeks. The plastic covering encourages germination by maintaining high soil moisture and raising soil temperature. However, it excludes light, and emerging weed seedlings cannot survive for long in the dark. When the mulch is removed before crop planting, the seedbed is clear of weeds and remains weed-free for an extended period.

It has been shown that the exclusion of light during seedbed preparation itself is also a practical way to reduce weed numbers. Buried seeds of many weed species require the brief exposure to light that they receive during soil cultivation, to trigger germination. Simply covering the cultivating implement with a light-proof shroud to prevent light reaching the soil at the moment of cultivation may be sufficient. Cultivation in darkness has been shown to reduce weed emergence by up to 70%. However, it is often much less effective because not all weed species have seeds that are light-sensitive, and even the seeds of normally responsive species can lose their light requirement with age. Also, small-seeded species like mayweeds (*Matricaria* spp.) that emerge from the surface layers of soil receive sufficient light to germinate anyway.

Tertiary tillage is essentially mechanical weed management in the growing crop, and will be discussed later with other methods of direct weed management. Once cropping has finished, a sequence of post-harvest cultivations can be planned that directly or indirectly benefit weed management. The depth of cultivation will determine whether potato tubers left after harvest remain near enough to the soil surface to be killed by frost. The timing of the first post-harvest cultivation can have a marked influence on the persistence of freshly shed weed and crop seeds. A strategy that extends the opportunity for seed predation can have a substantial and often underestimated effect on weed seed dynamics. It can also benefit the birds and insects that feed on seeds after harvest. The early burial of recently shed seed of oilseed rape can induce dormancy by instilling a light requirement and, as a consequence, prolong persistence in the seedbank. A two to three week interval after harvest is sufficient for the oilseed rape to begin germination and be killed by the delayed cultivation. With seed of some species, such as sterile brome (*Anisantha sterilis*), however, lengthy exposure to light on the soil surface will impose dormancy. This causes the seed to persist longer when eventually buried than does seed buried soon after crop harvest. Early cultivation is therefore advantageous if sterile brome is the main grass weed.

Cultivation as soon as practicable after harvest is also recommended for the management of rhizomatous grass weeds such as common couch (*Elytrigia repens*) and black bent (*Agrostis gigantea*). An intensive rotary cultivation is needed to work the soil to the full depth of the shallow rhizome system. The aim is to fragment the rhizomes to as small a size as possible, and this works better in previously undisturbed soil. Once the soil has been cultivated, further passes at this time only serve to move the cut rhizomes around. Fragmentation stimulates regrowth of a dormant bud on each rhizome fragment. Cultivations to manage regrowth may be repeated every two to three weeks or when the grass has leaves 5–10 cm long, until no further regeneration occurs. Alternatively, the land may be ploughed to bury the regrowth, or a cover-crop may be sown to smother it. The aim is to exhaust the food reserves in the vegetative organs and prevent accumulation of additional reserves.

Direct weed management

Direct weed management is based primarily on mechanical and thermal methods, and on the use of mulches. At high weed densities, even the most effective direct weeding tool will often leave sufficient weeds to survive and reduce crop yield. Direct management must be linked with long-term preventative measures to maintain the weed population at a manageable level. In an established crop, the problem is to manage weeds selectively without injuring the crop itself. At its simplest this can be achieved by hand-pulling or hoeing of the emerged weeds. Different types of shields can be fitted to protect crop foliage from damage by mechanical and thermal weeders, and from being covered with soil. These may take the form of discs, plates or protective hoods.

Guidance and weed-detection systems have been developed to make faster, more accurate and more effective use of direct weeders by detecting the position of the crop row or individual weed or crop plants. Laser transmitters and receivers have been used to guide tractor-mounted machinery in a straight line across a field, to allow seedbed preparation and mechanical weed management operations to be carried out day or night. More complex guidance systems use image analysis to find and follow the crop rows by tracking row structures. Some plant-detection systems have included image analysis based on leaf shape. Other systems use spectral sensing or light reflectance to discriminate between crop and weeds. An automatic guidance system is unlikely to be cheap but there could be reduced labour costs. The choice of implement and weeding method depends on practical aspects such as the crop and the soil type, but economic elements like purchase price, operating costs and labour requirements are often the over-riding factors.

Mechanical weed management

The most effective mechanical method of weed management is complete burial of seedling weeds to 1 cm depth, or to cut them at or just below the soil surface. Mechanical weeders range from basic hand-held tools to sophisticated tractor-driven devices. They include cultivation implements such as hoes, harrows, tines and brush weeders, and cutting tools such as mowers and strimmers, as well as implements like thistle-bars that do both. Drawbacks to mechanical weeding include low work rate, delays due to weather conditions, and the risk of failure as weeds become larger.

The choice of implement depends on the range of crops being grown. Fixed harrows are more suitable for use in arable crops, while inter-row brush weeders are considered more effective for horticultural use. Management may be aimed at the whole cropping area, or it may be limited to selective inter-row weeding. In widely spaced crops planted 'on the square', a second inter-row weeding may be possible at right angles to the first. In addition, some inter-row weeding tools are designed to direct soil along the crop row and thus bury small intra-row weeds.

The optimum timing and frequency of weeding operations depends on the size and species composition of the weeds, the choice of weeding implement and the crop itself. Weeds are more likely to be killed by weeding at early growth stages but this may not result in good overall management if later-germinating weeds are missed. The relative performance of different implements often varies at different plant growth stages and different tractor speeds. In winter cereals, weeds which develop a deep taproot are more effectively managed using spring-tines in the autumn before the weeds become well established. Leafy weeds with branched roots are managed better in spring when there is more foliage to catch on the tines. A single early inter-row cultivation may provide excellent weed management in a crop like transplanted broccoli that rapidly develops a broad, shading leaf canopy, but more prolonged measures may be needed in less competitive crops where early development is slow or when there is a long growing season.

Hand tools

Hand removal or roguing of a single plant or patch of weed is often the most effective way to prevent that weed from increasing to become a serious problem. In established grassland, hand-pulling or digging out of weeds is generally regarded as impracticable except for light infestations. Hand hoes, push hoes and other traditional methods of hand-weeding are still used on horticultural crops in the UK. Hand-weeding is often used after mechanical inter-row weeding to deal with the weeds left in the crop row. To improve the efficiency of overall hand-weeding, a tractor-drawn platform that extends across several plant rows may be towed slowly through the crop, carrying a team of workers lying prone and weeding on the move.

Harrows and tines

The use of harrows will bury small annual weeds but is ineffective against perennial and established deep-rooted weeds. Spring-tine and other tine weeders, and chain or drag harrows, may be used for overall 'blind' or pre-emergent harrowing carried out after drilling but before crop emergence in order to kill the early flush of weeds. The method is most successful if applied between weed seed germination and the cotyledon stage. The aim is to increase selectivity in subsequent weeding operations by giving the crop an advantage over the weeds. Dry weather is critical to the success of early harrowing operations but adequate soil moisture is needed to ensure early weed emergence.

Tine weeders, with rigid or spring-loaded tines, superficially cultivate the whole soil surface and are considered less damaging to a cereal crop than chain weeders. Those with blocks of tines in separate units are able to follow the contours of the land. The tines bury small weed seedlings under loose soil but do not pull up cereal plants beyond the three-leaf stage. The choice of tines depends on soil type, and adjustment of the implement, especially the angle of penetration of the tines, is also important. Depth can be managed and, on some machines, additional pressure can be applied hydraulically to the tine units to allow the weeder to adapt to soil conditions. Tine weeders are more successful on lighter soils and are less suitable for heavy land. Weed management is said to improve as tractor speed is increased, but crop damage may also increase. Weeders with flexible tines can be used selectively at the late-tillering stage of cereals when the dense crop foliage forces the tines into the inter-row. In broad-leaved crops, flexi-tine weeders may injure poorly established crop plants and reduce yield. Torsion weeders with sprung tines will give a measure of selective inter-row weed management with less risk of damage.

The rolling cultivator with ground-driven 'star' or 'spider-tine' rotors also allows inter-row weed management. The rotors can be angled to move soil away from the crop row, or to ridge up the crop with soil and bury small weeds; but this is effective only if the crop is taller than the weeds. Selectivity with tine weeders of any sort is always greater when the crop has a size advantage over the weeds. Other factors that influence the degree of selectivity include site characteristics, the composition of the weed flora and moisture levels at and immediately after harrowing. The introduction of finger weeders with flexible rubber tines on a ground-driven cone wheel has improved within-row weed management further. These are designed to take out small emerging weeds along the crop row, but need to operate in loosened soil and are usually fitted behind a hoe. Rotating heads of robust vertical metal tines are used to cultivate around and between plants in the row in established tree and staked perennial crops.

Steerage and tractor hoes

Hoes undercut weeds and are more effective than tines against mature weeds. Tractor hoes may have 'A'- and/or 'L'-shaped fixed, vibrating or revolving shares that cut through the soil at 2–4 cm depth. Goose- or ducks-foot shares may be mounted on individual parallelogram linkages or fitted to individual spring-tines. A shallow working depth and relatively steep position of the hoe blade often give the best results. Increasing the working depth does little to improve weed kill with a hoe, but greater forward speed increases soil covering of weeds after hoeing and reduces survival. Hoe blades may also be followed by simple ground-driven rotors that lift the cut weeds onto the soil surface to dry out and die. Desiccation is a critical factor in preventing regeneration, and wet conditions after hoeing can decrease the level of weed kill. Soil structure is also important; in rough or capped soil, weeds may continue to grow in the clods or plates of soil lifted by the hoe.

Hoes are used to manage inter-row weeds selectively but the shares undercut everything, so a second operator or some form of self-steering mechanism is needed to ensure careful guidance between the crop rows. A good seedbed and precise drilling of crop rows are prerequisites for success. Harrowing-in of cereal seed after drilling may displace the seed out of the row, leading to crop damage during hoeing. Inter-row hoeing may lead to some reduction of crop density in narrow row spacings or following early weeding treatments, but this may not affect yield. Seed rates can be increased to compensate for any likely losses. In cereals, increasing the row spacing from 12 to 20 cm facilitates inter-row cultivation, without affecting yield appreciably. In root crops like carrot and sugar beet, implements may incorporate ridging bodies and earthing bodies to bury weeds along the row with a band of loose soil. The hoe-ridger is specifically designed to do this in sugar beet and other row crops, giving a mixture of inter- and intra-row weed management.

The powered rotary hoe is fitted with rotating 'L'-shaped blades on a horizontal axle or as individually suspended units. Cultivation of the soil is very rigorous and it is able to manage established weeds. Rotary cultivation is particularly effective in fragmenting the vegetative organs of perennial weeds. A cycle which allows regrowth followed by further cultivation aims to exhaust the food reserves of the weeds. The working width of the rotary hoe units can be adjusted to different row spacings for inter-row weeding. However, the root system of some shallow-rooted crops may be injured by intensive inter-row cultivation. Weed management does not improve with faster forward speed of the rotary hoes, and the machine works best on light, stone-free soils.

Other mechanical weeders with a hoe-like action which lift out or undercut weeds just beneath the soil surface include thistle-bars and basket-weeders. Thistle-bars are simple blades that are pulled through the soil to undercut perennial weeds with minimal soil disturbance. Custom-made basket-weeders, with gangs of rolling wire cylinders, loosen and lift out the weeds but are effective only against small seedlings in a fine dry soil.

Brush weeders

The weeding action of the brush weeder, or brush hoe comes from strong nylon brushes that rotate and brush the weeds out and onto the soil surface. Two main types of brush weeder have been developed; those with brushes operating horizontally and those with brushes operating vertically. In the former, brush position on the drive shaft and brush width can be adjusted to different row widths. It is primarily intended for inter-row weeding of vegetable crops although it has been used in cereals. The foliage of crop plants can suffer mechanical damage from contact with the brushes. To prevent injury, shields or hoods may be fitted that protect each side of the row. It can operate with moister soil conditions than a tractor steerage hoe. The brush weeder uproots the weeds and working depth is the most important factor in ensuring good weed management. Tractor speed, brush velocity and soil conditions interact to determine the working depth. A second operator is needed to ensure careful guidance of the brushes between the crop rows. The brush weeder with vertical heads can also be used for inter-row weeding. The brushes can be angled and the direction of rotation altered to move soil towards the row to earth up the crop plants. Small weeds that the brushes cannot reach within the crop row are buried giving some within-row weed management. A finger weeder fitted with plastic brushes instead of rubber fingers has been developed for flicking out the weeds along the crop row.

Mowers, cutters and strimmers

Flail, rotary and reciprocating knife mowers have been used to manage perennial broad-leaved weeds in grassland, or simply to reduce vegetation height and prevent succession to scrub in amenity areas. For selective weed management, the timing, frequency and height of cutting are critical to exhaust the vegetative organs and, in some species, to prevent seed production. In grassland, however, cutting may simply encourage prostrate growth of some weeds. In arable and vegetable crops, hand-held and wheeled strimmers offer the potential to cut down seedling and larger weeds pre-crop emergence, or post-crop emergence between the plant rows, without disturbing the soil surface. An experimental inter-row strimmer has been developed that can be used on several rows at a time. Where weeds are taller than the crop, weeds may be topped to prevent further seeding, as an alternative to hand-roguing. A machine based on a rape swather, with the cutter bar set just above crop height, has been used to top wild oats (*Avena fatua*) in cereals. After cutting, the weed is pushed into a collecting tray for disposal.

Novel mechanical weeders

Some novel weeding equipment has been devised by agricultural engineers or purpose-built by growers, but few new systems are put into general production. One implement that is being developed injects compressed air into the soil to loosen and uproot small weeds on either side of the crop row. This has been used successfully in carrot, maize and sugar beet.

Thermal weed management

Stubble burning, now banned, was the traditional form of thermal weed management used to reduce the number of viable weed seeds returned to the soil after cereal harvest. Managed burning has also been used for vegetation management in amenity and industrial areas. Current methods of thermal weed management use a variety of energy sources to generate the high temperatures needed to kill weed seeds and seedlings.

Flame weeding

Flame weeding machinery has now achieved a high level of sophistication. The main fuel used is liquefied petroleum gas (LPG), usually propane. The gas is fed to a series of burners set beneath a metal canopy. Flame weeding kills by an intense wave of heat that ruptures the plant cells. It is necessarily a foliar contact treatment and only the exposed plant tissues may be disrupted initially. There is no residual effect of flaming and a single treatment may not maintain management of weeds through a full season. Long-term weed management depends on whether the injured plants recover and on the extent of subsequent weed emergence. To perform a second flaming may be more effective than a single treatment. Flame weeding can prove more economic than hand-weeding but initially there is a high machine cost. Flame weeders have the advantage that they can be used when the soil is too wet for mechanical weeding.

Flame weeders can be used for total vegetation management, for selective weed management and for foliar desiccation of crops such as potato before harvest. Selective weeding may be achieved by flaming the early flush of weed seedlings before the crop emerges. Timing is critical to ensure maximum weed kill but treatment must not be left so late that emerging crop seedlings are damaged. Pre-emergence flaming in carrots and in the umbelliferous herbs coriander, dill and parsley has reduced weed numbers by up to 80%. Flame weeding has little effect on weed seeds within the upper layer of soil and does not appear to reduce subsequent weed emergence. However, unlike mechanical methods of weed management, there is no soil disturbance to stimulate a further weed flush.

Once the crop has emerged, selective inter-row weeding may be achieved by angling or shielding the burners. Alternatively, the dose may be adjusted to a level that the crop will tolerate. Flame weeding is thought to be unsuitable for crops with shallow or sensitive root systems. Studies to determine the optimum design of flame weeders suggest that shielding design is critical to keep the hot gases close to the ground for as long as possible. The angle of the burners is also important; an angle to the horizontal of 22.5° to 45° is best. The selectivity of post-emergence inter-row flaming depends in part on directing the heat towards the weeds while avoiding damage to the crop foliage.

Plant size at treatment has a major influence on the response of plants to flaming and on the dose required for management. All weed species are more susceptible at earlier growth stages, but grass weeds such as annual meadow grass (*Poa annua*) with a basal growing point are more resistant to flaming than are broad-leaved weeds. Onions, too, have a basal growing point and drilled, transplanted and set-grown onions can tolerate post-emergence flaming. Transplanted cabbage with its waxy leaves has some tolerance to heat, allowing band flaming along the crop row. However, damage can occur when treatment is applied too early. In young orchards, where treatment can start on a clean soil after cultivation, flaming may keep annual weeds in check, but in an old orchard management of established perennial weeds will be transient at best.

Some flame weeders use infrared heat or a combination of infrared and direct flaming to kill the weeds. The burners heat ceramic or metal surfaces to produce infrared radiation (IR) that is then directed at the target weeds. The infrared heat is thought to penetrate deeper into the plant tissues and can be focused on a more closely defined area than heat from a standard flame weeder.

Steaming

Mobile steaming equipment is now available to manage weeds and pathogens in polytunnels and in the field. Steam under pressure is applied beneath metal pans forced down onto freshly formed beds for periods of 3–8 min. The steam raises the soil temperature to 70–100°C, killing most weed seeds to a depth of at least 10 cm. Only clover (*Trifolium* spp.) and other hard-seeded legumes appear resistant to this treatment. Weed seeds in the soil below the treated layer are unaffected and will germinate if the soil is disturbed to that depth. However, if there is no further cultivation following treatment, weed management can remain effective for two seasons. The machinery is slow moving and work rates of 40–100 h/ha of treated bed are likely. At present, field steam sterilisation is not allowed under the UK organic guidelines. Jets of steam can also be used to kill emerged weeds directly. Machinery has been developed for use in amenity areas as an alternative to the application of herbicides.

Direct heat

Machinery is also available for killing pests, diseases and weed seeds in field soil using dry heat. A worked ridge of soil is lifted, passed through a chamber heated to 68–70°C by a diesel-fired burner, and then deposited back onto the ground in a reformed ridge. The depth of treatment required depends on the crop. It ranges from 10 cm for shallow-rooted crops to 25 cm for potatoes. The dry heat system is slow but allows faster coverage of an area than field steaming. The work rate for treating a 15 cm depth of soil is 1–2 ha/day, depending on soil type.

Solarisation

Soil solarisation uses the Sun's energy to kill weed seeds in the surface layer of soil. It requires a moist seedbed to be covered for around six weeks with clear plastic sheeting to trap solar radiation and heat up the soil. Seeds more than 5 cm below the soil surface are unlikely to be killed and soil disturbance should be avoided after treatment. A climate with long periods of clear skies and sunshine is needed to maintain a sufficiently high temperature (> 65°C) under the covers for long enough to kill the weed seeds. Weed development is likely to be enhanced rather than impeded under clear polyethylene covers in the cooler and cloudier conditions that prevail in northern Europe. Soil temperatures under plastic covers depend on the thermal characteristics of the sheeting in addition to the intensity of incoming radiation. Transparent plastics differ in their light transmittance characteristics and this may affect their soil-heating ability. There is a possibility that adjusting the light-transmitting quality of plastic sheeting to provide greater retention, or conversion of light radiation to heat, could warm the soil sufficiently to kill weed seeds at lower light levels.

Mulching

Weed-seed germination and seedling emergence can be suppressed by covering or mulching the soil surface to exclude light. Mulches are generally less effective against established perennial weeds that have sufficient food reserves to emerge through all but the most impenetrable materials. A mulch may take many forms: a living plant ground cover, loose particles of organic or inorganic matter spread over soil, and sheets of artificial or natural materials laid on the soil surface. Spray-on mulches have been developed that form a thin latex-based film over the soil, but these are intended primarily for stabilising loose soil. The residue from a preceding crop may be left after harvest to form a mulch into which a succeeding crop is planted. Different mulches can be combined, e.g. plastic sheeting laid along the plant row or bed, and straw spread in the inter-rows and along tractor wheelings. Sheeted mulches may be used as an alternative to cultivation to kill vegetation before cropping. It has been shown that a range of covering materials left in place for 12 to 18 months can be used to clear an established grass pasture prior to planting vegetables. In general, the high cost of mulching makes it economic only for high-value crops or for perennial crops where a mulch is expected to last for several years.

Living mulches

A living mulch consists ideally of a dense stand of low-growing plants established before or after cropping. Often, the purpose is not limited to weed suppression. Other objectives may be to improve soil structure, aid fertility or reduce pest problems. In cereals, an understorey of clover improves soil fertility and reduces pest and disease problems in addition to suppressing weeds. The successful application of a living mulch requires careful management. When the growth of a living mulch is not restricted, or when soil moisture is inadequate, the crop will suffer competition and loss of yield. Living mulches are well suited for use in perennial crops such as fruit where the inclusion of self-reseeding species can be an advantage. However, even in established orchards, a living mulch growing along the planted row may depress crop growth. It has been argued that careful management of certain low-growing weeds could provide a ground cover that would inhibit the growth of other weeds.

Particle mulches

Loose materials can provide effective weed management but the depth of mulch needed to suppress weed emergence is likely to make transport costs prohibitive unless the material is produced on site. A layer of compost 3–5 cm deep is needed to prevent the emergence of annual weeds. The most widely used organic materials include straw, bark and composted green waste. Weed seeds in the mulch itself can be a problem if the composting process has not been fully effective or if there is contamination by wind-blown seeds. In straw mulches, volunteer cereal seedlings are a particular problem because of shed cereal grains and even whole ears remaining in the straw after harvest. With particle mulches that consist of light materials, there is the possibility that strong winds will expose bare soil. The decomposition of mulches made from organic materials may result in the release of natural phytotoxins or the locking up of soil nitrogen. Both can have a negative effect on crop growth and yield. Straw and bark mulches applied along the tree row have been shown to manage weeds effectively in orchards in the first year of use. However, weed numbers increased in the second year. Also in the second year, there was a reduction in soil mineral nitrogen concentrations associated with decomposition of the organic matter, under both mulches.

Sheeted mulches

Black polyethylene mulches are widely used for weed management in organic and conventional systems. Plastic mulches have been developed that selectively filter out the photosynthetically active radiation (PAR) but let through infrared light to warm the soil. These infrared-transmitting (IRT) mulches have been shown to be effective in managing weeds. Various colours of woven and solid film plastics have been tested in the field. White and green coverings had little effect on the weeds; brown, black, blue, and white on black (double-colour) films prevented weeds emerging.

In the UK, black polyethylene mulch has given excellent weed management and increased yields of transplanted sprouts and calabrese. In apples, black polypropylene woven mulch laid along the crop row gave almost complete weed management and higher crop yield than other mulching and chemical treatments. Paper mulches have compared favourably with black polyethylene in transplanted lettuce, Chinese cabbage and calabrese. Brown and black paper mulches have given good weed management in salad and flower crops. There may be problems in laying some mulches, with the wind lifting and tearing the sheeting. With paper mulches, correct laying followed by rapid crop establishment is the key to avoid tearing and wind blow. The stretching or contracting that follows changes in moisture levels can cause a smooth paper mulch to tear. A crêped paper mulch has the flexibility to allow for this movement and is less likely to split.

After cropping, lifting and disposal may be a problem with plastic and other durable mulches. Paper, non-woven natural fibre and degradable plastic mulches have the advantage of breaking down naturally, and can be incorporated into the soil after use. There are additional environmental benefits if a mulch is made from recycled materials.

Biological weed management

The term 'biological management' in its widest sense could be taken to include practices such as crop rotation but it is usually restricted to the deliberate release of a natural management agent. Classical (or inoculative) management describes the introduction of host-specific, exotic natural enemies to manage alien weeds. Inundative (or augmentative) management involves the mass production and release of (usually) native, natural enemies against (usually) native weeds. Conservative management is an indirect method whereby the natural levels of the pests and diseases that attack the native biomanagement agents that feed on the target weed are reduced to a low level. This is a long-term strategy that requires a detailed knowledge of the ecology of all the organisms involved. Broad-spectrum management (or total vegetation management), as the name implies, rarely relates to a single weed and often refers to modification of a whole habitat.

Biological management would appear to be the natural solution for weed management in organic agriculture. Organic growers have readily adopted traditional broad-spectrum measures using grazing animals such as sheep to maintain a pasture or to aid spring weed management in cereals. Grazing is also used for vegetation management in country parks and other sites where the animals can be contained. The choice of grazing animal may provide some management of the composition of the resulting vegetation. Sheep are more selective than cattle but horses are even more particular in their grazing habits. There is also considerable potential for developing the concept of conservative biological management in organic systems.

Classical biological management with insects and with micro-organisms has been successfully applied in South Africa, Australia, the USA and elsewhere, and it continues to be an important area of study. It has been suggested that some of the introduced, invasive perennial weeds such as giant hogweed (*Heracleum mantegazzium*), Himalayan balsam (*Impatiens glandulifera*) and the Japanese knotweeds (*Reynoutria* spp.) would be ideal candidates for classical biological management. Attempts to use the caterpillars of two species of South African moth as biomanagement agents against bracken (*Pteridium aquilinum*) in the UK were unsuccessful because of the unfavourable climate. It is essential that non-native potential biomanagement agents are tested thoroughly for host specificity so that they do not pose a threat to other plant species. There are also opportunities for encouraging the action of native biomanagement agents against emerged weeds, and for enhancing the activity of indigenous pathogens in soil to manipulate or deplete the weed seed bank at source.

Inundative biological management uses native organisms, but there is the same requirement for host specificity as there would be with an introduced agent. Host specificity is increased when the susceptibility of the target organism can be enhanced. It may even allow a selected area of a weed to be managed without affecting nearby plants of the same species. Isolates of *Xanthomonas campestris* pv. *poae* cause bacterial wilt in annual meadow grass (*Poa annua*), a lawn weed;

however, the inoculum is taken up more readily through cut surfaces. Mowing prior to treatment increases the susceptibility of the weed within a target area. There can also be synergistic effects between two pathogens. In groundsel (*Senecio vulgaris*), plants naturally infected with the rust *Puccinia lagenophorae* are killed by inoculation with the pathogen *Botrytis cinerea*, while healthy plants are not.

Inundative biological agents, particularly mycoherbicides, can be applied as sprays in the same way as conventional herbicides. However, although mycoherbicides have offered much promise there are still many technical difficulties to overcome in their culture, storage and application. A biological agent often needs very specific conditions to be effective. In experiments with the mycoherbicide *Ascochyta caulina*, the correct plant growth stage and high humidity after treatment were shown to be critical in ensuring good management of fat-hen (*Chenopodium album*). Bioherbicides also have the dual hurdles of meeting the regulations that apply to biological management agents as well as those that apply to a conventional pesticide.

The application of biological management is not without controversy. The prediction of how biological management may affect the interaction between species, and influence the life cycle of non-target species, is extremely complicated. The assessment of the extent of the potential risks posed by biological management remains a contentious issue. For example, it may be difficult to predict the host range of pathogens that result from hybridisation between normally isolated, but closely related, microorganisms. Even when there is no risk to non-target species, there may still be a conflict of interests. While some perceive a particular plant, e.g. wild camomile (*Matricaria recutita*), as a common weed others see it as a desirable wildflower, or even a potential crop. In the USA biological agents were introduced to manage St John's Wort (*Hypericum perforatum*) but this is now grown widely as an ingredient for homeopathic medicines. There is also concern about the unrestricted spread of biological agents beyond the target area. The accidental introduction of the rust *Puccinia lagenophorae* into the UK demonstrates the potential for worldwide dispersal. The rust is of Australian origin and was unknown in Europe before 1960; however, it has since been recorded in France and the UK on groundsel (*Senecio vulgaris*).

Biological control is covered more fully in Chapter 17.

Allelopathy

Allelopathy can be regarded as a component of biological management. It refers to the direct or indirect chemical effect of one plant on the germination, growth or development of neighbouring plants. Some studies have suggested that allelochemicals may be present in the mucilage around a germinating seed, in leachates from the aerial parts of plants, in exudates from plant roots, in volatile emissions from growing plants and also among decomposing plant residues where microorganisms may also be involved.

Allelopathic plants or their residues may not only inhibit the growth of weeds, but also reduce the germination and development of drilled crops, and may even check the growth of transplanted crops. Weeds that have allelopathic ability (like fat-hen, *Chenopodium album*) may inhibit crop growth both physically and chemically. Such weeds can also inhibit the growth of other weeds. Equally, any crop which had allelopathic ability might reduce the emergence of those weeds which were difficult to remove in the crop row, leaving only the inter-row weeds to be managed mechanically. Crops and their cultivars are known to differ both in their allelopathic ability and in their tolerance to the allelochemicals produced by other plants.

In agriculture, the evidence for allelopathy has come largely from studies of the use of organic mulches and cover crops to suppress weed emergence. Living mulches, intercrops or smother crops may provide physical weed suppression but their effect might in part depend on allelopathic ability. After incorporation, the decomposition products of organic mulches and cover crop residues may continue to prove phytotoxic in subsequent crops.

The use of techniques that might allow genetic transfer of allelopathic ability into crop plants is unlikely to be acceptable in organic practice. Another approach is to identify crops that contain chemicals or their precursors with the potential to suppress weeds. The glucosinolates, precursors of several toxic metabolites including isothiocynates, for example, are found principally among members of the *Brassicaceae*. The role of these secondary plant metabolites seems to be to deter feeding by animals, both vertebrate grazers and insect feeders. There is the potential to use brassicas as an alternative to soil fumigants for weed, pathogen and nematode management.

There have been suggestions that the allelochemicals themselves or synthetic derivatives could form the basis of bioherbicides. The concept of isolation and application of the toxin responsible for killing the weeds as a 'natural herbicide', rather than applying the living organism, has also been a consideration in the development of mycoherbicides. A range of plant derivatives are also being developed as potential bioherbicides. However, the application of these 'natural chemicals' may be seen by some as equivalent to applying their synthetic counterparts.

Integrated weed management

The concept of integrated weed management can mean different things to different people. In the same way that combining cultural and direct weed management can improve weed management within the rotation, integrating two or more direct weeding methods in combination, or in sequence, can improve weed management in the immediate crop. Inter-row brush weeding in carrots followed by hand-weeding from a mobile platform makes the most efficient use of resources to deal with both inter- and intra-row weeds. In the same way, a prototype machine that combines on-row flaming with inter-row hoeing in a single operation achieves full weed management coverage but reduces the high cost of overall thermal applications. Mechanical cultivation followed by intercropping can extend the period of weed management. For example, a sequence of tine cultivations followed by interseeding with ground-covering crops has been used to suppress weeds in transplanted cabbage. It is important that growers maintain a flexible approach to weed management and apply appropriate combinations of techniques to deal with particular weed problems. Integrated weed management is the subject of Chapter 14.

Weed biology

The different aspects of weed biology are dealt with in detail in Chapters 1–4, but it is worth emphasising here that there should be a much closer liaison between weed biologists and those concerned with weed management. The use by growers of the results from studies of the seasonal emergence patterns of common weeds is an example of the early application of weed biology. On arable land, the largest contribution to the soil seed bank each year comes from the weed and crop plants present in the field. The magnitude and species composition of the weed seed bank is a measure of the success or failure of weed management programmes, and provides guidance on future weed management strategies. Any weed management or cropping strategy that affects the composition of the emerged weed population is likely to influence the contributions made to the seed bank during and after cropping.

There have been numerous studies of weed competition in arable and horticultural crops. In the past, there was criticism that little practical use had been made of the information from such studies. In cereals, one aim has been to identify the threshold at which the cost of weed management outweighs the benefits (the economic threshold). Thresholds are usually associated with herbicide treatments, but the same principle can be used to determine the economics of applying a non-chemical weeding treatment. In cereals, it has often been reported that although mechanical weeding treatments have reduced weed numbers or weed biomass, there has been no gain in crop yield. There may be some merit in defining the weed pressure that a particular crop can withstand before yield loss occurs (the physiological threshold). In considering the long-term value of non-chemical weed management measures, however, the threshold concept may not be realistic. In the organic system, the spectre of unrestricted seed return and the potential for increasing future weed problems are likely to outweigh deliberations on the economics of applying a particular weed management measure.

In field vegetables, even low numbers of weeds have been shown to reduce yield, and crop quality and marketability may also be affected. However, experiments have shown that a crop does not need to be weed-free from sowing until harvest to prevent loss of yield due to weeds (see also Chapter 2). In competitive crops a single, carefully timed weeding may be sufficient to avoid yield loss. Any advantage that increases the competitive ability of the crop or puts the weeds at a disadvantage may achieve a ‘weeding window’ in which a single weeding at any time will prevent yield loss. This gives greater flexibility in the timing of weeding operations. Studies to determine the critical or optimum weeding periods under conventional and organic growing systems have been made in some horticultural and arable crops. The defined optimum weeding times for some horticultural crops are given in Table 14.1. In carrot and onion, the same optimum weeding times were equally effective in crops grown organically and conventionally. Seed bank determinations in these studies have shown that limiting weed management to a single, carefully timed weeding does not necessarily lead to an increase in the weed seed bank after harvest.

Table 13.1 Optimum weeding times for horticultural crops grown under European conditions

Crop	Production method	Optimum weeding time
Bean (broad)	drilled	Weed once at 3 wk after 50% crop emergence
Beet (red)	drilled	Weed once at 4 wk after 50% crop emergence
Beet (sugar)	drilled	Weed once 4–6 wk after 50% emergence
Cabbage (summer)	drilled	Weed once at 3 wk after 50% crop emergence
Cabbage (summer)	transplanted	Weed once 3–8 wk after planting
Carrot	drilled	Weed once at 4 wk after 50% crop emergence
Lettuce (summer)	drilled	Weed once at 3 wk after 50% crop emergence
Onion (bulb)	drilled	Weed from 6–8 wk after 50% emergence
Onion (bulb)	transplanted	Weed once 4–6 wk after planting
Onion (salad)	drilled	Weed once at 5 wk after 50% crop emergence
Potato (main)	planted	Weed once 2–8 wk after planting
Radish	drilled	No weeding needed
Raspberry	planted	At cane emergence in May
Swede	drilled	Weed once 2–4 wk after 50% emergence
Turnip	drilled	Weed once 2–4 wk after 50% emergence

Adapted from Turner *et al.* (1999).

Crop–weed competition models have been developed that have a practical application in predicting likely yield losses from particular weed populations, and in indicating critical or optimum weeding periods for given crop–weed combinations. For practical purposes, models that predict yield loss need to be based on a parameter that can be readily measured at an early stage so that appropriate remedial action can be taken. Competition models can also be used with cover-crops, living mulches and inter-crops to determine the best mixtures and planting arrangements for optimum yields and good weed suppression. Even the characteristics that are likely to give the crop a competitive edge over the weeds can be determined using modelling studies. The combination of weed-seed production, seed movement, seedling emergence and weed competition models will form the basis of future decision-support systems for achieving effective weed and crop management both in the longer term and in the immediate crop.

Conclusions

The present chapter has dealt solely with non-chemical methods of weed management. In reduced and low-input farming systems, limited or appropriate use of herbicides remains an integral part of the approach. Nevertheless, cultural and direct non-chemical weed management can make an important contribution to reducing chemical inputs within such systems. There are many opportunities, e.g. where the integration of chemical and non-chemical methods can reduce either the dose or the area of herbicide application. An initial mechanical weeding that puts weeds under stress allows a reduced dose of herbicide to be as effective as the full dose on the surviving weeds. The combination of mechanical inter-row weeding with band-spraying of a full rate of herbicide along the crop row can reduce the treated area and hence herbicide input by more than 50%.

It is recognised that direct methods of non-chemical weed management alone are often not sufficient to manage weeds effectively, and in the organic farming system such measures are sometimes viewed as the final resort. The primary means of weed management are the cultural measures that form an integral part of crop rotation. However, the crop and the production system remain the overriding factors that determine the practical and economic feasibility of applying particular methods of direct non-chemical weed management. While some methods favour large-acreage arable crops, others are only feasible for low-acreage, high-value horticultural crops. Different techniques of weed management may be appropriate for perennial crops like top and soft fruit, and for grassland. It is important that specialised areas of organic or low-input farming are not neglected. Nor should relatively expensive management methods like mulches be dismissed because they are uneconomic in large-acreage arable crops. Integration of cropping and weed management strategies is vital for the future success of farming systems that rely on non-chemical methods of weed management.

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Chapter 14
Integrated Weed Management

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Introduction

Great improvements in agricultural efficiency and productivity over the past 50 years have made it possible to supply plentiful wholesome, high-quality, affordable food throughout the year to much of the Western World. Adoption of new technologies in machinery, plant breeding, fertilisers and pesticides has led to sophisticated and specialised farming systems. However, in some instances the increased productivity has been associated with a loss of rural wildlife and habitats. Increasingly farmers are faced with the need to make decisions to ensure a healthy and competitive crop grown in balance with nature. This means weighing up the value of weeds as a food source and habitat for invertebrates and vertebrates adding to the wider conservation resource, alongside their threat to plant health.

Biodiversity

About 300 species of wild plants are found in arable land but efficient systems of weed management have led to a decline in their occurrence. Many of these species are ruderals, adapted to exploiting the bare ground created annually by cultivation. In 1990, a UK survey found five and seven species per 200 m^2 plot in the eastern arable lowlands and the western pastoral lowlands respectively. Some arable weeds are now exceedingly rare and restricted in their distribution. For example, *Ranunculus arvensis* (corn buttercup) is difficult to find even though its almost exclusive habitat, fields of winter cereals, is relatively widespread.

In 1994 the UK Biodiversity Action Plan (BAP) set challenging, but attainable overall goals for biodiversity conservation: ‘to conserve and enhance biological diversity within the UK and to contribute to the conservation of global biodiversity through all appropriate mechanisms’. The Priority List of the UK Biodiversity Action Plan contains 62 species of higher plants, 14 of which are found exclusively or mainly in arable land. The wider UK BAP List of Species of

Conservation Concern contains 159 species of which 24 occur predominantly on farmland. In addition the weeds in a crop provide a valuable food resource and habitat for invertebrates and vertebrates and so provide a wider conservation resource. Thus, there is increasing importance placed on attaining the targets of the UK BAP as an integral part of decision making on farm.

The industrial guru Sir John Harvey Jones has said that 'the pursuit of better, more environmentally friendly, methods of production will bring business rewards in their own right'. Although he was referring to businesses in general, this comment applies equally to farming, where there have been significant improvements in environmental responsibility in aspects of agricultural technology such as machinery, plant breeding and pesticides. Attention to detail and more-informed decision making on farms has led to reduced risks of pollution and cost savings through carrying out activities only when necessary. These improvements are akin to the principles of integrated farm management.

However, the public does not appreciate this and instead sees agriculture as the polluter of the countryside. Certainly, it is not appreciated that farming is the provider of the produce on the supermarket shelves. However, with numerous food and health scares, there continues to be much concern about farming practices and there is a widening gap between the farming community and the public. This adverse public opinion has led to a number of political reactions in Europe. For example, Sweden, Denmark and Holland have imposed mandatory reduction targets of 50% in the use of pesticides. Furthermore, Denmark and Belgium have introduced taxes to reduce pesticide use. At Community level the Nitrate Directive requires Member States to limit nitrates coming from manures and inorganic sources. In the UK this has resulted in the designation of Nitrate Vulnerable Zones (NVZs). Thus, in order to avoid further regulations and directives it is increasingly important for farmers to put into practice and demonstrate responsible farm management systems.

Integrated weed management

In Britain, the LEAF organisation (Linking Environment And Farming) is doing just that. Part of a European network, the European Initiative for Sustainable Agriculture (EISA), LEAF develops and promotes Integrated Farm Management (IFM) as a means of combining effective, safe and economic production systems with consideration to conserve and if possible enhance the rural environment. The core concept of IFM is the management of all the farm resources in order to obtain sustainable and profitable businesses. This system focuses on careful analysis of the farm resources, with appreciation of the limitations imposed by the location, to derive an appraisal of the agronomic potential. Within IFM, one component is Integrated Crop Management (ICM) but it is important to relate this to the whole farm and to examine the relationships with animal and other enterprises.

There are many definitions of ICM, some of which are:

- The efficient profitable production of crops in harmony with nature for our benefit and that of future generations
- A holistic pattern of land use which integrates natural resources and regulation mechanisms into farming practices to achieve a maximum, but stepwise, replacement of off-farm inputs to secure high-quality food and to sustain income
- A whole-farm policy, combining rotations with targeted use of pesticides and fertilisers, cultivation choice and variety selection, together with a positive management plan of landscape and wildlife features
- A comprehensive system of modern husbandry practices
- Balancing economic production with environmental responsibility
- The choice of a balanced crop rotation which can reduce pest, disease and weed problems while maintaining soil structure and fertility
- A cropping strategy in which the farmer seeks to conserve and enhance the environment while economically producing safe wholesome food; its long-term aim being to optimise the needs of consumers, society, the environment and the farmer
- A combination of responsible farming practices which balance the economic production of crops with measures which conserve and enhance the environment
- The concept of a viable agriculture which is environmentally and socially acceptable and ensures the continuity of supply of wholesome, affordable food while conserving and enhancing the fabric and wildlife of the British countryside for future generations
- A proven crop rotation backed up by judicious management whose aim is to keep inputs to a minimum while maintaining profitability at conventional farming levels
- A concept which blends the best of traditional farming methods with the environmentally sensitive use of modern technology
- A management system which employs controlled inputs to achieve sustained profitability with minimum environmental impact, but with sufficient flexibility to meet natural and market challenges economically

Common to all of these definitions are concerns of ‘environmental responsibility’, ‘social acceptability’ and ‘ecological sensitivity’, ‘economic viability’ and the ‘production of safe, quality food’. ICM is a flexible, site-specific management system for the whole farm that balances these features with running an economically viable business to produce high-quality food. It involves all aspects of crop production, including soil management, crop protection, energy efficiency, organisation and planning, biodiversity etc. Weed management is one part of crop protection. It is a strategy based on an evaluation of the decision-making process, identifying and evaluating any action needed and recording achievements made.

Integrated is the key word. The physical features of a farm, such as its topography, buildings and climate, cannot be altered. Within these constraints, ICM guides the selection of farming practices. For *crop* systems, the ICM approach considers all aspects of crop husbandry, including the use of crop rotations and appropriate soil cultivations, together with the judicious use of fertilisers and pesticides, the selection of appropriate variety, drilling date, harvest and storage methods and marketing. Crucially the combination of these aspects has a focus of protecting and enhancing the environment. ICM provides a systematic framework for crop *management* involving thoughtful planning, setting targets and monitoring achievement, and critical appraisal of performance. ICM is thus skills-intensive rather than input-intensive farming. This does not necessarily mean that inputs must be reduced, but that they should certainly be optimised to achieve maximum benefit with minimum environmental impact – applied if they are needed, where they are needed and when they are needed.

Within ICM, weed management is clearly one important aspect. This chapter aims to show how weed management strategies can incorporate all the options available to the grower into an integrated system, how they are part of the overall ICM and thus how they contribute to and draw from the other aspects of ICM. For simplicity we will call such an approach Integrated Weed Management (IWM) in the rest of the chapter. Importantly, we should distinguish weed management from weed control or weed eradication, so as to ensure that the crop is not challenged by competition but that wildlife is healthy.

IWM strategy

An IWM strategy is not a set of hard and fast rules but a set of guidelines to follow in the particular and unique circumstances of any particular farm. It addresses the fundamentals of best practice, and is also concerned with attention to detail; important actions in the development of an IWM strategy are:

(1) Ensure correct identification of the weed species which are present
(2) Evaluate the role of crop residue management
(3) Consider the different effects of soil cultivation methods on the weed seed bank and on weed populations
(4) Consider incorporating stale seedbeds before sowing
(5) Choose a more competitive crop variety
(6) Consider mechanical methods of weed management
(7) Use an economic threshold, not a cosmetic one.
(8) Map heavy infestations or recurrent infestations to allow for specialised patch treatment
(9) Consider the role of weeds in harbouring beneficial species
(10) Consider weeds as a wildlife resource

A key approach is to try to minimise the occurrence of weed problems in crops, and to manage weed populations using cultural and biological as well as chemical solutions. Management decisions contributing to the development of IWM on a farm are crop rotations, soil and cultivation practices, crop nutrition strategy, other aspects of crop protection, planning, crop hygiene, well-informed and trained staff, and wildlife and landscape management. Developing an IWM strategy for a farm involves getting to know what weeds are present and where they are so that treatment can be targeted, and prioritising which species must be managed and which can be tolerated. This information allows the development of a system involving prevention through exploiting the germination ecology of those weed species present and exploiting the competitive effects of the crops. In addition, the identification of economic thresholds to help set the priorities of the IWM and incorporating several methods of weed management including cultivation choice, timing of operations and the use of herbicides, are necessary. An important activity is to monitor the changes in weed flora so that the IWM system can evolve.

Soil and cultivation practices

Sound soil management practices not only can lead to improved crop establishment but also can contribute greatly to reduction of the weed seed bank in the soil. One aim of an IWM system is to minimise the likelihood of weed seeds shedding onto the surface of the soil and becoming incorporated into the weed seed bank in the soil. This will influence decisions on residue management from the previous crop and soil cultivation. A second aim is to minimise the weed seedlings which emerge in the growing crop. This may involve the deliberate encouragement of weed-seed germination prior to crop sowing (or transplanting) by using a stale-seedbed technique (cultivation followed by a contact herbicide) or through the choice of a later sowing date. Furthermore, the rotation of different cultivation techniques associated with different crop species can contribute to weed management. For example, the contrast between ploughing and non-inversion techniques helps to provide a non-consistent environment for ruderal weed species. Techniques which minimise soil disturbance can reduce the incorporation of weed seeds into the seed bank, reduce the return of buried seeds to near the surface where they might germinate, and reduce the environmental cues for germination (brief exposure to light, higher oxygen/carbon dioxide ratios, greater temperature fluctuation). However, the choice of soil management techniques will involve consideration of whether the technique encourages specific weeds. Most annual grass weeds appear to be favoured by reduced-tillage systems. Ploughing helps to minimise the occurrence of barren brome but reduced tillage has little effect on populations of this species.

Crop rotations

A wide crop rotation can make a great contribution to weed management because of the different timings of sowing, canopy development and harvesting of the crop within which the weeds grow. The ease of control of different weeds in different crops also makes an important contribution to the development of a weed management strategy. Rotation creates a crop environment which is not consistent from year to year and consequently will not favour the development of large populations of any one weed species. Conversely it may permit the survival of a larger range of weed species some of which may be of wildlife or aesthetic benefit, albeit possibly more difficult to control. Under-sowing of grass leys into cereals can help to suppress the growth of weed species. Rotation of crops and the associated rotation of cultivations are powerful tools in the management of herbicide-resistant weeds, and indeed in minimising their evolution (Chapter 11).

Choice of variety

We have become aware again of the contribution which competition from the crop can make to weed suppression. There is a strong inverse relationship between crop biomass and weed biomass, so that bulkier varieties are more weed-suppressive. Also, crop varieties which intercept more light and minimise the penetration of light through the canopy provide a poorer environment for weed growth. Variety choice is an important consideration in the decision-making process of IWM. Choosing the right variety depends not just on yield potential but on crop health considerations. The recommended lists of cereals provide information on leafiness and tillering ability which both relate to canopy development and thus to weed-suppressive ability. In addition, selection of varieties with good resistance to those pests and diseases likely to be encountered on the farm will help to provide healthy, vigorous crops able to suppress weed growth. Canopy management of the crop is becoming increasingly important for cost-effective fertilizer use and has a clear contribution to make to shading weeds.

Seed purity

All seed for commercial sale has to reach certain minimum standards of purity (freedom from seeds other than of the variety named) and health (freedom from carrying pests or diseases). The high seed quality of most commercial seed lots ensures uniform, vigorous emergence of crop seedlings and good stand establishment when the seeds are sown into appropriate seedbeds. Seed lots of high quality are of critical importance in crop stand establishment because they provide better crop stands than do poor seed lots when conditions for germination and establishment are sub-optimal. It may be a false economy to use farm-saved seeds unless the grower can be sure that the seed purity and health are high. Otherwise, weed seeds may be sown along with the crop into a prepared seedbed;

crop plants bearing disease or pests are more responsive to competition from weeds. If it is intended to use farm-saved seed, then it is important to identify clearly and mark out the area of the field from which this will be taken. The area should be checked regularly or, better, it should be inspected to ensure that it remains suitable: it must be free from weeds, pests and diseases and the seed should develop well. After harvest the seed should be dried and stored separately in satisfactory conditions (dry and cool); ideally, it should be tested for grain moisture, thousand-grain weight and germination capacity, and also for purity and freedom from diseases.

Crop establishment

Timing of sowing has a marked effect on the productivity of the crop and on pest and disease incidence as well as on weed populations. The yield potential in high-yielding systems is greater with early sowing. Delay in sowing often incurs a yield penalty. Nevertheless, it has also increased the risk of weeds, diseases and pests. Often high yields are achieved with the expense of high inputs and the economic margin may be no greater than with lower input systems. It is important to consider the overall costs of production when considering an expected target yield. Considerable benefits can be obtained from delaying sowing because it may permit the development of only a relatively sparse weed population and also reduce the risk of fungal infection. However, there may be difficulties for weed management with late autumn sowings if, in order to prevent soil compaction, access to land is precluded by the weather conditions.

Crop nutrition strategy

Maintaining soil fertility to meet crop requirements is the key to successful and profitable crop management. However, the inappropriate use of inorganic fertilisers, and in particular organic manures such as slurries, can lead to excessive nutrient losses from soil to air and water, with consequences for the local and global environment. Luxury application of nutrients may simply help to grow bigger weeds which produce more seeds. Thus, it is important to develop a farm nutrient management strategy which plans to balance or replace nutrient inputs with offtake and reduce the nutrients available for weed growth. Techniques such as foliar application of liquid nutrients should be able to supply nutrients selectively to the crop and not to the weeds.

Herbicide applications

IWM allows the use of herbicides as one of the weapons in the armoury to combat weeds. It is regarded as essential that it is not the first, nor the only, method for weed management. IFM systems will often involve the use of less herbicide. In the Boxworth project, fields following an IFM strategy required on average 2.6 herbicide applications a year whereas fields with a 'full insurance' strategy of herbicide use had 4.9 applications. Inevitably, this represented a cost saving through better targeting of inputs to where and when they were needed. The different herbicide policies led to different weed floras: on this farm there were mainly broad-leaved weeds in the 'full insurance' fields and more grass weeds in the 'integrated' fields.

Other aspects of crop protection

Accurate identification of the weed species present is an essential prerequisite to weed management. It is important to have a full knowledge of the weed's biology in formulating an IWM strategy. Regular inspections of the crop permit the estimation of the size of the growing weed population and hence rational decisions on whether or not to apply specific measures to be based on a threshold approach. Seeking advice from a BASIS-registered agronomist may help to ensure that the correct decision is made. It is essential to ensure that the threshold is an economic one rather than a cosmetic one.

Generally a healthy crop is more vigorous and can better shade weeds. Crop plants which are suffering from diseases or pests are less able to compete strongly with weeds. IFM and therefore IWM strategies emphasise that prophylactic applications of herbicides should only be used where and when it is certain that they are absolutely necessary and offer safe, effective solutions.

Natural biological control

Commercial applications of biological control have mainly been developed in fruit and protected cropping systems. The available systems are currently too costly and not effective enough for use in arable crops. However, the establishment of wildlife features such as beetle banks and conservation headlands may supply organisms which feed on the weed species in the field. More details on the biological control of weeds are given in Chapter 17.

Wildlife and landscape management

Selective and planned IWM can not only provide financial benefits due to better attention to detail, it can also benefit the environment. Establishment of unsprayed field margins or conservation headlands at the edges of fields can reduce the costs of application of chemicals and the costs of any cultivations carried out because the treated area is smaller. The preponderance of perennial species in unsprayed margins and conservation headlands tends to resist colonisation of crops by many of the annual weeds and so the risk of enhanced annual weed populations is low. Potentially, these areas provide a source of weed seeds for the main area of the crop but there may also be advantages from the occurrence of beneficial organisms which may help to manage weeds, pests and diseases. More effective weed control on farms has been a major factor in the decline of farmland birds. One approach encouraged through IWM is the establishment of habitats in and around field edges which are of low yield potential. These can provide habitats for small weed populations and play a part in conserving rural biodiversity.

Pollution control

The IFM approach places emphasis on ensuring that where herbicides are used they are used safely and effectively. This means it is important to make sure that staff are aware of the risks and precautions necessary for their own health and for the health of the general public, of wildlife and of the environment. Well-maintained equipment needs to be operated by trained staff, avoiding drift (see Chapter 10) and spraying of sensitive areas such as field margins, hedgerows and watercourses. All this leads to a more professional approach and one which results in the production of safe, high-quality food and other farm products, grown with concern for the environment.

Conclusions

It is not necessary to eradicate weeds. Farms are businesses whose outputs are primary products. It is tempting to maximise output and there is much technical information to assist with this. Nevertheless, the business imperative should be to optimise output and maximise profit. This goal does not require that weeds (and other negative factors in crop production) be eliminated, rather that their impact be reduced to an acceptable level to benefit the crop and contribute to the environment. The approach of IWM emphasises the long-term nature of weed populations and so threshold values for weed populations occurring in a single crop are not appropriate. Instead, the effort and the cost have to be set against the whole rotation. In the process of thinking about the crop management decisions, a range of options become available, i.e. the set of tools in the weed management kit is enlarged. Thus, IWM aims to replace reactive chemical control with thoughtful weed management.

Key points

- Integrated weed management recognises the need to manage weed populations
- This can be done thoughtfully, incorporating weed management into all parts of the cropping system
- IWM can give environmental benefits

Chapter 15
Developing Decision-Support Systems to Improve Weed Management

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Introduction

Other chapters in this book have shown that optimised weed management is a complex combination of weed biology (including cultural factors) and herbicide use. Recent farming systems projects in the UK – TALISMAN (Towards A Lower Input System of Managing Agrochemicals and Nitrogen), IFS (Integrated Farming Systems), LIFE (Less Intensive Farming and Environment) – have all demonstrated the importance of weeds as a constraint to more integrated and cost-effective farming methods. One key aspect of weeds, which makes them different from most pests and diseases, is that the consequences of control practices in one year impact on subsequent crops in the rotation.

Weed control has always been a combination of rotational and individual crop approaches and farmers control weeds for six major reasons:

- To protect crop yield
- To protect crop quality
- To ensure ease of harvest
- To prevent problems in following crops
- To reduce spread of pests and diseases
- Pride

Because of these complexities, the limitations of existing information and other issues (such as pride in a clean crop), farmers and advisers are very reluctant to reduce inputs. However, there is real scope to do so. There is therefore a need to provide farmers and advisers with better guidance on how to optimise levels of weed control. However, it is also essential to maintain profitability, to identify requirements accurately and target herbicide use, to minimise the risks of herbicide resistance and finally to provide opportunities to conserve rare weeds and/or uncompetitive populations of those species with wildlife or environmental benefit.

Development of decision-support systems for weeds

A number of knowledge-based systems for crop protection have been developed. Some are more comprehensive than others. Many of the earlier weed control expert systems were little more than herbicide use guides and give little cost/benefit information. Uptake by the farming industry of these earlier Decision-Support Systems (DSSs) has been poor, often because an adviser or farmer could generate the same information with a little experience, without the use of the DSS. It is critical that the DSS is able to provide answers to complex problems that would have been very difficult or impossible to solve without the use of the system. Almost all the systems attempt to answer two questions: what is the need for weed control (cost of control versus loss in profits caused by the weeds), and how do I achieve the desired level of control? There are several problems associated with the production of a weed DSS. In many situations there is a dearth of reliable information on the biology, population dynamics and competitive ability of common weeds. Current systems all depend on estimates of weed density to calculate yield responses, and there is a problem in deciding how to survey a field adequately to collect this information without taking an uneconomically long time. This problem is even more severe when weed infestation level is based on estimates of the weed seed bank.

There have been two contrasting approaches to the development of weed expert systems, with some concentrating on herbicide and dose selection and others concentrating mainly on weed competition and the need for control. The expertise and background of the research group tends to influence the orientation of the DSS. More advanced systems attempt to combine the two aspects of weed competition and population dynamics studies with herbicide dose selection. A further division in the structure of the current DSSs lies in their selection of herbicides for inclusion. Some systems offer advice only on post-emergence weed control, as the DSS relies on visual observations of the densities of plants of the weed species present to decide on control strategies. Other systems support decisions of pre- and post-emergence herbicide treatments, linking weed seed bank estimations to herbicide choice.

The only weeds information within the UK is contained in the development of a DSS for spring barley. This project is not yet complete, but is very valuable in having established some principles for designing a weeds DSS for UK conditions. The currently available expert systems concentrate on the main crops in the relevant countries, such as cereals, oilseed rape, soybean or maize. The structures of all these systems are of considerable relevance to the development of other systems but the actual information included in the system will only be relevant where the data are accurate in the countries for which it is designed. In general, where the DSS is primarily concerned with post-emergence weed control the current systems require the user to specify various data. An estimate of the weed species and their infestation levels (generally density) is a first requirement. Crop vigour and perhaps emergence date, together with the expected weed-free yields and crop price, help to set the output side of an economic context with the input side needing information on herbicide prices. In addition, weed size and climatic conditions (e.g. moisture levels) are important for estimating the effectiveness of weed management measures.

The programmes estimate potential losses in profitability due to the presence of weeds and offer suggestions of herbicide products that could be used, indicating their economic benefit. Systems will identify appropriate doses of selected products and indicate which species are the most difficult to control. In the most developed systems, information is available on almost all common weed species.

Until now, user uptake of DSSs has not generally been great. This is not always the case. For instance, some are now an accepted source of information on weed control and manufacturers enthusiastically supply information on their new products for the database, to ensure that they are included in the annual updates. There is also interest in the development of DSSs for weed management in many countries. Some of these initiatives have failed whilst others are still at an early stage of development. Some are being led by weed biologists/herbicide specialists, whilst others seem to be driven by the availability of appropriate computer technology. The reduced list of registered (and therefore permitted) herbicides (Chapters 7 and 19) could create a demand from growers for a DSS which integrates all aspects of weed management.

Information needed by weed decision makers

It is absolutely vital that any decision-support system meets the needs of those who are going to use it. The major users of any system will be those who make weed control decisions on farms, whether they are advisers or farmers. In addition, such a system would be of value to policymakers and as a training aid.

The development of a weed management support system started in the UK in October 2000. As part of the first phase, potential users have been asked to identify their needs. This demonstrated there was a clear demand for help with making strategic decisions which balanced cultural aspects with herbicide strategy over several seasons, and looked at implications in future crops. Fine-tuning of herbicide performance on the day of spraying was of interest but was of lower priority. There was a demand for herbicide dose information, but probably based on bands rather than on detailed dose curves. Another clear requirement was for greater herbicide selectivity information than is available on most product labels. In particular any information on activity, even that insufficient to allow a claim for control in the regulatory process, was demanded for a wide range of species. Similarly, the information that a product is known to give no control of a species should be readily available.

It was also obvious that the cost effectiveness of decisions was vital, but it was also interesting that the reliability of the strategy was more important than cost. Any decision aid increasingly must consider the implications for herbicide resistance and where possible should help evaluate the economics and implications of resistance management strategies. There was some demand for information which helps weed identification, provided that it offers the user a benefit over existing information.

It is also important to appreciate other factors raised in these groups. One very important aspect is that 'fear of getting it wrong' is still very critical, more so than designing a system which fine-tunes the correct management strategy. Users were generally content with assessing weeds on a number per square metre basis, but any additional help that modern technology could offer by way of a visual 'ready reckoner' for weed populations would be useful. Other items of great import to users were that any system should remember information input previously, it should allow tailoring to specific requirements and it must not be cluttered with information not required for the enquiry under consideration.

Integrating with other systems

Weeds are only one aspect of crop management. Other decision-support systems have been developed (wheat disease manager), are being developed (spring barley, oilseed rape pests and diseases) or will be developed. It is absolutely vital that they are integrated and also able to draw on datasets collated and maintained from other systems.

A system has already been developed in the UK, called DESSAC (Decision-Support System for Arable Crops). DESSAC is designed to be an integrated system which provides support for a number of decisions made during the production of arable and other field crops. It comprises a generic decision-support system called the DESSAC Shell, which embodies the general framework for the development of DSSs. When the DESSAC Shell is marketed, a purchaser will be able to obtain one or more specific DSS modules and 'plug' them into the Shell. The DESSAC Software Developers Kit (SDK) enables specific decision-support modules to be developed and to be compatible with the Shell.

The DESSAC Shell provides the infrastructure in which to operate a DSS. Specifically, the shell will provide access to the following data for DSSs:

- *Farm data*, which may be stored in a basic farm management system provided with the shell, or extracted from the user's farm management system
- *Weather data*, which may be available in many forms, such as long-term national or local averages, weather generators or farm-specific data
- *Encyclopaedic data*, e.g. general reference information such as the pesticide guide, will be part of the DESSAC Shell; each DSS module will provide its own specific set(s) of encyclopaedic information
- *Growth stage data*, from which growth stage models can be run to allow the crop growth to be estimated and checked with the user.

The DESSAC Shell provides the following facilities:

- *Browser:* A multi-page browser provides access to the encyclopaedic information, together with a DESSAC help system and a report layout service for the DSS modules; the information is presented as structured text with images that can be browsed using hypertext links and hot-spots, or searched using keywords
- *System navigation:* Standard mechanisms allow the user to navigate through the system to access the various facilities.
- *Data navigation:* Standard mechanisms allow the user to navigate through the data to select specific sets of data, e.g. to select weather data for a specified region for a particular period of time or to navigate through the farm data to enable fields or crops to be selected either individually or in blocks
- *Weather viewer:* Existing weather data can be viewed in various formats, new data can be entered and existing data can be edited and saved to provide more weather sets
- *Scenario generator:* This facility allows the user to ascertain the effect of different conditions, such as weather, on the output from a DSS
- *Warning system:* This facility is used to build a list of planned tasks: the user is alerted to actions which have been planned but not entered as ‘carried out’ in the farm database
- *Combined decisions:* Several DSS modules can interact, if the DSS developers enable the feature, to provide a combination of decisions on related problems

The DESSAC SDK provides the following facilities for constructing decision-support modules:

- *Basic software components*, which are used to ensure compatibility of the DSS, with the shell
- *Data entry facilities*, providing a standard mechanism for entering and editing data in the system
- *Sequential decision analysis model*, to take the results of a process model and provide a ranked list of the best current decisions
- *Display facilities*, to display the results of the decision process in a standard intuitive manner
- *Mechanism for incorporating uncertainty*
- *Basic shell for testing the DSS*
- *Test harness*

Requirements for a weeds decision-support system

As has been suggested, it is essential that a weeds decision-support system reflects the needs of users. It is likely that it will need to allow users to plan and develop strategies for weed management and to make decisions in response to field observations from the current season. It should provide a strategic way of examining the consequences of a range of options, without being prescriptive, and permit the utilisation of past records to predict potential ones (i.e. herbicide resistance).

It is unlikely to be able to include all weed species in equal detail, so they will need to be classified into three groups: key; priority; and others relevant to the geographic area under consideration. Most data will be required for the 'key' weeds and least for the 'others'. For these key species a full, quantitative description of their biology and population dynamics together with detailed herbicide selectivity, dose, mixture and sequence information will be required to allow long-term strategic planning of weed control strategies. The other relevant weed species are likely to be best included on the basis of a simpler herbicide selectivity/cost basis. A key element of the DSS will be to establish a framework for making use of detailed biological and herbicidal information in a decision-support setting. It should be possible to expand the base of key species to encompass new problem weeds, or to include species of environmental or conservation importance.

A weeds DSS would encompass the following key aspects (Fig. 15.1):

- A strategic decision tool to determine the impact of cultural factors (cultivations, rotation, drilling dates etc.) and pre-drilling treatments on weed populations in all crops on a farm
- Encyclopaedic information on weeds and their biology
- Encyclopaedic information on herbicides
- A herbicide selection package based on the best information to improve herbicide choice, dose and timing in the current crop in order to improve herbicide efficacy

In particular, this will need to take account of the need for weed control (cost, yield, benefit) and permit optimising a selection of cultural practices, herbicide choice and dose. The optimisation is affected by weed size, the weed species present, the weather conditions for herbicide activity, any other herbicides used in sequence or mixture, the competitive ability of the crop and by environmental considerations.

The system will need to be flexible to accommodate specific priorities as well as economic and environmental constraints. Some of the critical aspects that need to be considered for inclusion are discussed below.

Herbicide efficacy data

The herbicide database within a weeds DSS will need to be large and detailed, and could prove to be one of the most important 'selling' points of the system. The herbicide data requirements will mean it will be necessary to:

- Develop a common efficacy score system within which all data sources can be integrated

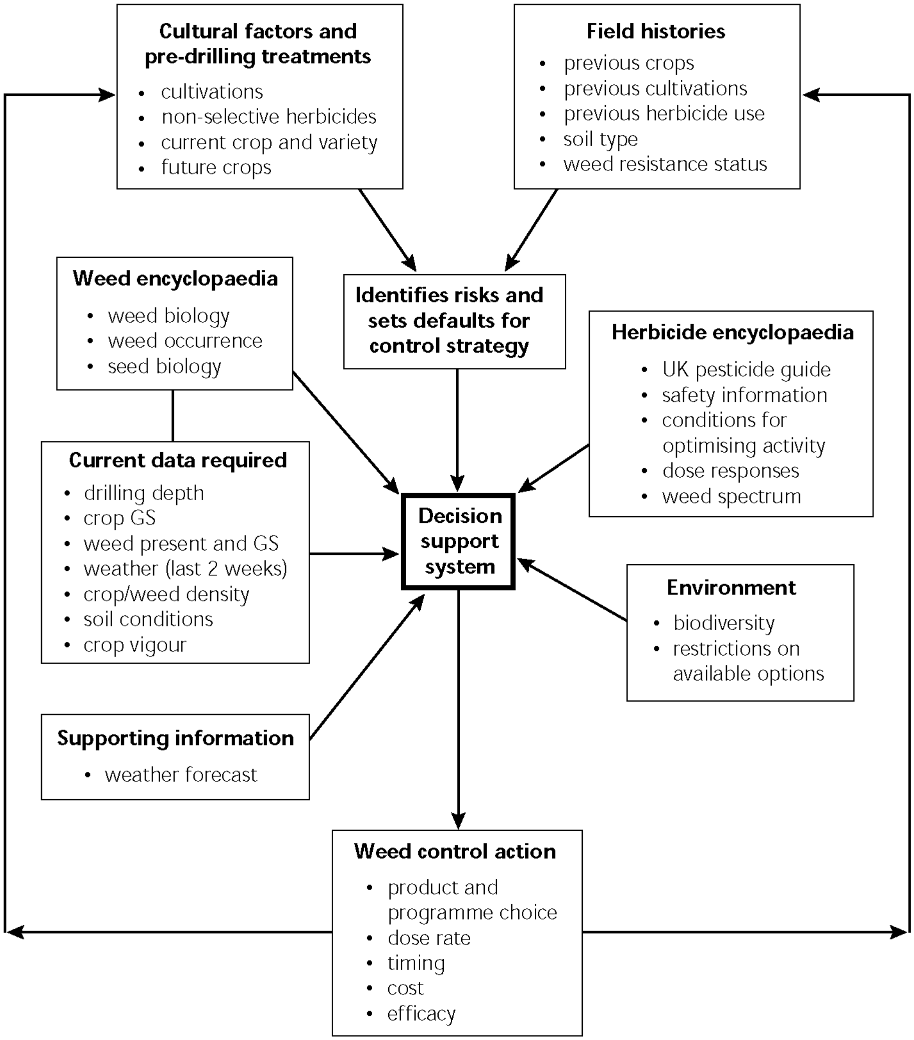

Fig. 15.1 A possible framework for a weed management DSS in UK.

- Produce a basic template for the database and a detailed description of each 'field' of data
- Produce specific databases for the levels of reliability required; this might be best considered as approved information from product labels, information supported by manufacturers but not on product labels and information which will never be supported by manufacturers
- Develop a template for environmental implication fields of information

Encyclopaedia of weed biology information

This will be critical to the decision advice provided by the weeds DSS. The encyclopaedia would represent a valuable resource for growers and consultants in its own right. All the weed species addressed will need to have an entry, but the most detailed information will be provided for the key weed species. Depending on the user requirements, the encyclopaedia could include:

- Photographs of weeds at different stages of their life cycle
- Detailed descriptions (and an identification key)
- Details of emergence patterns, seed biology and other life cycle information
- Geographic distribution data
- Ecological descriptions (soil types, climate)
- Environmental considerations (such as benefit to birds)
- Herbicide resistance information

Cultural and rotational information

For the key species where the emphasis is on long-term strategic planning, the consequences of rotation, cultivation and other agronomic practices will need to be included in the weeds DSS. This will involve compiling data in a usable format, in particular it will be necessary to:

- Consider effects of rotations, cultivation types and timing on seedling emergence using current information derived from the literature, existing simple biological population models and expert knowledge.
- Provide a dataset for the optimisation/selection of treatments using the same techniques as used for herbicide selection from the herbicide encyclopaedia.

Biological models

The biological modelling aspect will be key to the success of a weeds DSS as a tool for long-term strategic decision-making. The most important aspect of the models will be to include and quantify ‘risk’. Key parameters, such as weed-seed production, can be associated with a probability distribution. Changes in management alter the average value of such key parameters, and will change the associated probability distribution. It is this description of the changing probability for different outcomes that can result from a range of options which creates the opportunity to optimise weed management, and which will be needed to feed into economic cost/benefit models. The detail and complexity required for different weed species will differ. Information such as that given in other chapters of this book will be critical.

Decision modelling

There are three parts to the decision modelling: determining the need for weed control, herbicide selection for the set of weeds chosen by the user and optimisation for the strategically important weeds. These require distinct approaches. The models will need to integrate the risk of resistance using farm-specific information such as the resistance status of weeds, the farm cropping history, the pesticide usage history and the planned rotations. Some information will be derived from the databases created elsewhere in the weeds DSS; other data will need to be collected through a structured knowledge elicitation.

The need for weed control

Determination of the need for weed control will necessitate construction of simple, empirical models to predict the future weed population for a season, given previously observed weeds, soil and cropping information and climate. These would be used to estimate the cost of failing to control weeds through lost yield and loss of quality, e.g. as downgrading of crops through failure to meet quality parameters.

Strategy selection

Herbicide selection, or more generally strategy selection for Integrated Weed Management (IWM, see Chapter 14), will need to be through an evaluative model based on quantitative and qualitative data from pesticide registrations, published literature, trials and recognised agronomists.

Optimisation

The optimisation model will need to make use of the biological models for the key weed species. Because of the quality of the data, a quantitative approach is likely to be more appropriate. The model will need to be placed within finite boundaries. This should allow the optimisation of sequences of decisions to maximise a long-term objective, and it should produce a complete policy to respond to different states of the system at intermediate stages.

Evaluating the potential of the weeds DSS to meet user requirements

To ensure the quality and robustness of the advice provided by the weeds DSS, the individual components and their integration will need to be fully validated at all stages. The validation of model components could take two main forms. Model outcomes could be validated against experts to determine how the model's performance corresponds with expected outcomes. It might also be relevant to instigate some field experiments to test the model's performance in real situations, but this is very difficult for long-term implications. These sites would also provide a valuable role in demonstrating the abilities of the DSS.

Model validation could include testing the reliability of the predictive potential of the biological models in terms of control effectiveness and crop yield response for a number of weed management strategies and testing the ability of the model to predict rates of weed population expansion, given a number of management strategies. The biological models will need to be compared with sets of published or unpublished trials data that are independent of those used to develop them. They could also be evaluated by agronomists to ensure that the results are in accordance with field experience.

The optimisation will be dependent on the performance of the biological model, so validation of the model is crucial in ensuring that the recommendations it produces are correct. The performance of the 'optimiser' itself can be 'bench-tested' independently by evaluating all possible options in the model and ensuring that it is finding the best ones. In these tests the 'optimiser' could operate with perfect information, which will not be available in practice, where the future is always unknown.

Weed decisions for the future

Finally, the weeds DSS needs to be capable of being relevant in the future. For instance, in the UK it is predicted that rotations dominated by autumn cropping will continue to predominate, with oilseed rape as a major break crop, although it is likely that there will be more continuous cereals than at present. Common Agricultural Policy (CAP) reforms and economic pressures are likely to increase pressure to reduce fixed costs (cultivations, machinery, labour) and spread them over larger unit sizes. Thus managers will cover a larger area and will need either a simple approach to weed control or decision-support systems that are easy to use. It will also become more important to have a greater spread of drilling dates in autumn, to dilute fixed costs. This could result in a greater range of weed infestations and species present, complicating decision-making in terms of current and future crops. In addition we are likely to see an increase in demand for reduced cultivations to keep costs down. Reductions in labour and machinery will mean that cultural control measures will have to be clearly justified.

The technology already exists to allow patches of weeds to be sprayed within fields. Thresholds cannot easily be adopted on a field scale because of small-scale variations in weed numbers. Ultimately, spatial sensing and application offer the opportunity for spraying weeds according to local need rather than adopting the current practice of applying sufficient herbicide overall in order to control the highest local populations in the field. Improved weed management and opportunities for reducing herbicide use will be assisted by improved detection of weed patch distribution and more robust information on weed thresholds, for which demand is increasing. Thresholds need to account for long-term implications of leaving weeds as well as those within the crop.

The future challenge for research will be to allow the rational use of herbicides and to support competitive production while protecting the environment. Research on the biology and control of weeds will need to focus on strategies to improve herbicide targeting and reduce use, and to translate results into integrated weed and crop management strategies. A particular challenge will be the integration of weed management with environmental drivers such as the need to improve biodiversity and hence address the decline in farmland birds, other wildlife and flora. Although the current work provides a good base for addressing these issues, certain aspects will need more careful consideration. In particular various challenges must be tackled.

Can management options be developed for the 'aggressive' weeds so that they are retained at levels that farmers will tolerate, but that allow adequate populations of more desirable species? This should include the effects on population dynamics of incomplete control, e.g. with mechanical weeding or with sub-lethal doses of herbicides.

Can we demonstrate robustly to farmers and agronomists that leaving a few weeds does not matter? Could this be improved by demonstration of 'corrective measures' to reduce the risk? This needs to reflect the long-term implications, not just those for the current crop.

Can more selective weed management practices be developed – using either conventional herbicides which are more selective, bioherbicides or cultural methods – which will control aggressive weeds while maintaining beneficial species?

Weed control strategies will have to continue to take into account herbicide resistance, which will be a major challenge to the sustainability of current farming systems. Improved mechanical weeders may play an increased role in the future, to reduce herbicide use but also to allow control of larger weeds. Maintaining weed management options within non-cereal crops will increase in importance as herbicide options decline. In these crops more attention will need to be paid to non-herbicide options, including cultural measures and physical weed control. The role of herbicide-tolerant crops in changing weed management strategies will need to be assessed.

In summary, the future of arable cropping and demands for weed management are predicted to be influenced by:

- Winter dominated rotational cropping, especially wheat and oilseed rape;
- Increased use of reduced cultivations to control fixed costs;
- More early drilling to reduce or spread costs;
- Increase in unit size to spread costs;
- Increased demand for simple robust weed management strategies;
- Increased demand for sensing and threshold information to optimise herbicide doses;

- Increased demand to leave non-crop plants as sources of bird feed, for at least part of the season;
- Continued need to include resistance management in weed control strategies;
- Need to evaluate impact of herbicide tolerant crops on weeds and weed control strategies.

Key points

- It is essential that the requirements of users are clearly identified
- Strategic multi-season decisions are likely to be a major aspect
- It is essential to consider future issues
- Economic information is essential, but environmental issues are of increasing importance
- DSSs must integrate with the others available, and be compatible with other datasets
- Encyclopaedic information on weed biology and herbicides will be required
- Decision models which include handling risk are essential
- Validation of models will be critical

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Chapter 16
Optimising Herbicide Performance

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Introduction

Farmers in many northern European countries are facing an increasing pressure to optimise their use of pesticides. The public concern of possible effects on human health and the environment is one reason for this. In addition, the political decision to reduce subsidies within the EU and move towards world market prices is another incentive to farmers to reconsider practices they have used hitherto. In most northern European countries herbicides constitute the majority of the pesticides used in arable crops and so are targets for cost reduction by growers and for reduction on health and environmental grounds.

Optimising herbicide use implies that decision-making is improved. The first step in decision-making is to consider preventive measures such as crop rotation and growing competitive varieties to reduce the potential losses due to weeds. The second step is to assess the need to spray at the time of weed control (Chapters 13 and 14). If weed control is required, the third and last step is to choose the herbicide(s) to be used and the rate. In this chapter I will focus on the last of these three steps of decision-making.

Herbicide performance is affected by many biotic and physicochemical factors, and a basic understanding of the influence of some of the key factors is a prerequisite for optimising this performance. Most of the available information on the influence of variable factors on herbicide performance is qualitative, merely distinguishing between significant and non-significant differences. If farmers are going to implement this kind of information in their decision-making it is imperative that data of a more quantitative nature will be available. In this chapter I will describe the most important variable factors affecting herbicide performance and as far as possible illustrate this by giving examples where the effect of a particular factor was quantified.

Weed flora

It is well known that herbicide efficacy varies considerably between weed species. A detailed knowledge of the composition of the weed flora and a rough idea of the frequency of the weed species is crucial for making correct decisions on herbicide and dose rate. The bulk of herbicide efficacy data available to farmers and advisors merely classifies weed species as ‘controlled’, ‘partly controlled’ or ‘not controlled’ by a particular herbicide at a given standard dose. Unfortunately, in most countries very little information is available on the dose response of different weed species to even the most frequently used herbicides. Often, very large differences in susceptibility are found within the group of weeds classified as ‘controlled’. This is illustrated in Figure 16.1, showing the performance of two cereal herbicides applied at a range of doses.

At the dose recommended by the producer both herbicides controlled all five weed species (80% effect or higher), but whilst satisfactory control of some weed species required the recommended dose, others were controlled using one-sixteenth of the recommended dose (e.g. *Stellaria media* with chlorsulfuron and *Veronica persica* with ioxynil + bromoxynil). The pronounced differences among susceptible weed species means that substantial dose reductions are possible if the composition of the weed flora is determined before application (Fig. 16.1).

Furthermore, if the composition of the weed flora is known and if dose response information is available on the individual weed species, it is possible to reduce the costs of weed control even further by designing field-specific herbicide solutions. If, for example, the five weed species included in Fig. 16.1 are found in a field, a mixture consisting of low doses of chlorsulfuron and ioxynil +

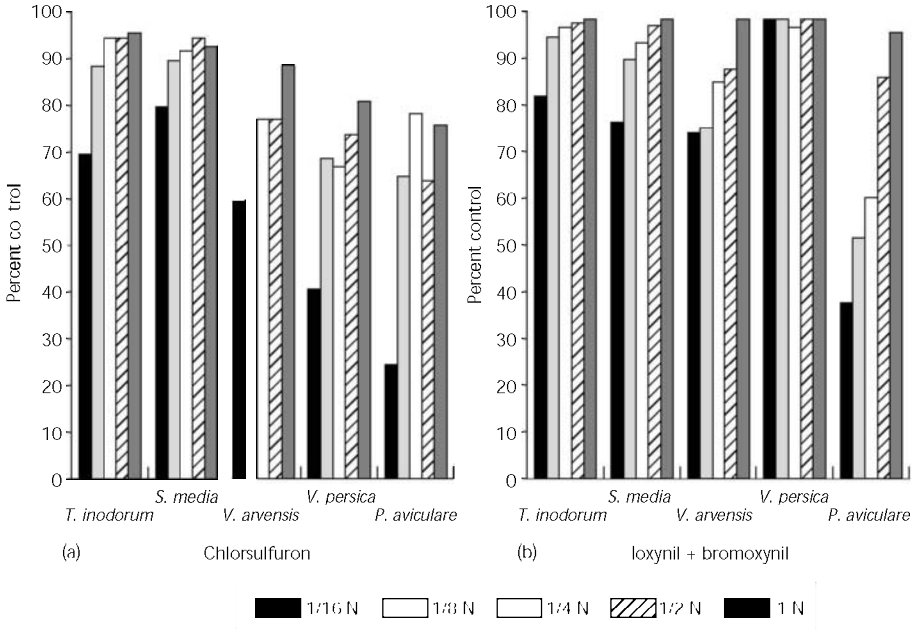

Fig. 16.1 Effect of chlorsulfuron ($N = 4$ g/ha) (a) and ioxynil + bromoxynil ($N = 400$ g/ha + 400 g/ha) (b) in two experiments in spring barley in Denmark.

bromoxynil seems to be an effective solution (see also the section below on 'Herbicide mixtures'). In practice, the obstacle for most farmers to exploit fully the differences in herbicide performance on various weeds is correct weed identification, and this aspect should attract much more attention in the future.

Growth stage of weeds and weed density

Annual broad-leaved weed species, generally, are more susceptible to herbicides at the early growth stages than later, although there are exceptions. For example, the susceptibility of *Galium aparine* to herbicides such as mecoprop and fluroxypyr does not vary significantly within a wide range of growth stages. For grass weeds susceptibility to some foliage-applied herbicides increases with growth stage until the two- to three-leaf stage, after which herbicide performance tends to decline. For example, application of some of the wild oat herbicides at the very early growth stages only controls the main shoot; some of the tillers survive and eventually produce seeds. Another factor to consider is whether the weeds constitute a sufficient target for foliage-applied herbicides. This could be a problem particularly with grass weeds because the first leaf tends to be more erect and therefore spray retention can be expected to be lower than on the subsequent leaves, which are more prostrate. In contrast, numerous experiments with broad-leaved weed herbicides have shown that even very small weeds seem to constitute a sufficient target. Germination pattern is another parameter to take into account. Foliage-applied herbicides should not be applied until the majority of the weeds have germinated. However, under dry soil conditions weeds tend to germinate over a longer period and herbicide application may have to be delayed. In less competitive crops, exploiting the benefits of spraying at early growth stages is only possible by shifting from a single-application strategy to a split-application strategy.

Weed growth stage is generally considered to be a more critical factor for soil-applied than for foliage-applied herbicides. Among the foliage-applied herbicides the response to non-systemic herbicides such as the phenylureas and the hydroxybenzonitriles is believed to be more dependent on growth stage than systemic herbicides such as the phenoxyalkanoic acids and sulphonylureas. Figure 16.2 summarises results from pot experiments examining the influence of weed growth stage on the performance of pendimethalin, a soil-applied herbicide, ioxynil + bromoxynil, a non-systemic foliage-applied herbicide, and tribenuron, a systemic foliage-applied herbicide. The weed species used as test plants in the experiments differed in their susceptibility to different herbicides but they were all considered to be susceptible to the particular herbicides under test. The results confirmed that the response to soil-applied pendimethalin was more dependent on growth stage than that of the two foliage-applied herbicides. Comparing the two foliage-applied herbicides, the response to the non-systemic herbicide, ioxynil + bromoxynil, was more dependent on growth stage than the systemic herbicide, tribenuron.

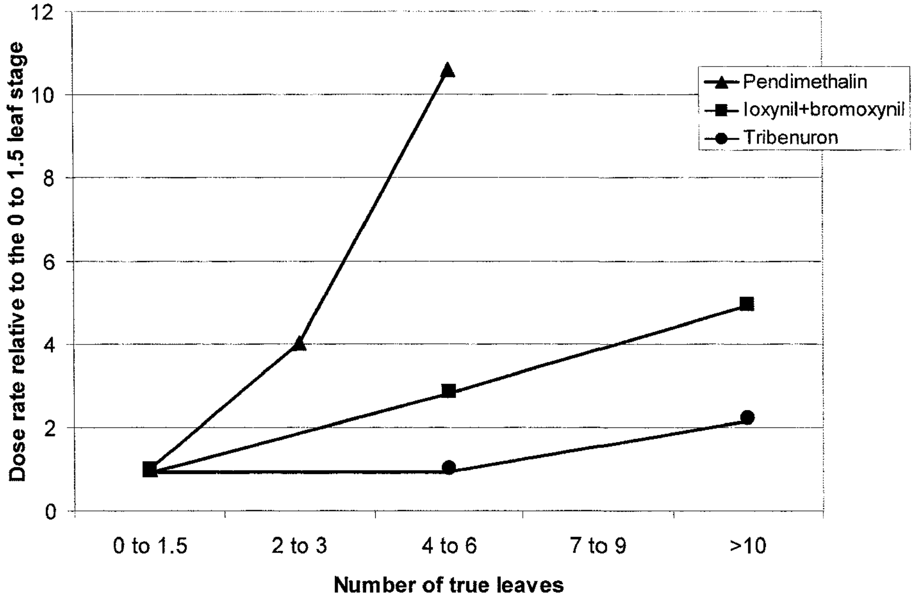

Fig. 16.2 Summary of results of pot experiments examining the influence of growth stage on the performance of pendimethalin (five experiments), ioxynil + bromoxynil and tribenuron (four experiments with each herbicide).

Because of the pronounced influence of growth stage of annual weeds on the performance of most herbicides, the optimum time of application allowing for reduced doses is at the early growth stages of the weeds.

Weed density has been shown to affect the performance of soil-applied herbicides in pot experiments. At high weed densities each plant absorbs less herbicide than at low densities. Whether this is also the case under field conditions is more doubtful because herbicide uptake is normally not considered a major route for removal from the soil. At high weed densities the performance of foliage-applied herbicides can be expected to be reduced because leaves of individual plants overlap, reducing the target exposed to the herbicide.

Depth of germination may affect the performance of soil-applied herbicides. Weed species able to germinate from greater depths are more likely to survive a herbicide treatment than weed species germinating from the upper soil layer, as illustrated for the herbicide diflufenican + flurtamon in Fig. 16.3. This is also the reason for the variable effect of (for example) trifluralin against *Avena fatua* and *Galium aparine*, which can both germinate from 5 to 10 cm depth.

In contrast to annual weed species, perennial weed species like *Elytrigia repens*, *Cirsium arvense* and *Artemisia vulgaris* are normally controlled most effectively at specific growth stages which often coincide with the time of maximum translocation of assimilates to the subterranean plant organs.

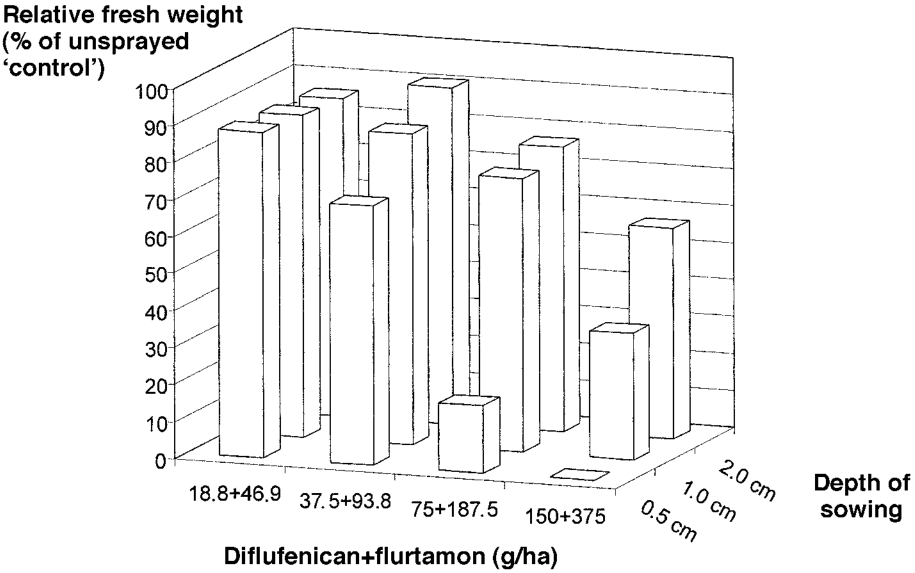

Fig. 16.3 Influence of depth of sowing on the effect of diflufenican + flurtamon on *Lolium perenne* (data from a pot experiment).

Climatic conditions

It is well known that the performance of many herbicides is affected by the climatic conditions before, at and after herbicide application. Climatic conditions affect the growth and physiological status of the weed and crop, the herbicide and thus the plant–herbicide interactions. Climatic conditions around the time of application are generally considered one of the key parameters affecting herbicide activity and the cause of much variation in herbicide performance.

Most studies on climatic conditions have been done under controlled or semi-controlled conditions allowing for the manipulation of one climatic parameter while the others are kept constant. Such studies allow for a ranking of the climatic parameters, but their relevance to practice is questionable as it is difficult to extrapolate the results to the more complex climatic situation in the field, where climatic parameters fluctuate (e.g. temperature, humidity and light) and some of them interact (e.g. temperature and humidity). In fact, despite the abundance of information on the role of climatic parameters in herbicide performance, this information has not been widely used to adjust herbicide doses to the prevailing climatic conditions. If results from studies under controlled conditions are to be implemented in practice to optimise herbicide dose, it is important to be able to mimic natural conditions more precisely. In this section not only the effects on herbicide performance of some of the most important climatic parameters will be discussed but also alternative approaches to studying the influence of climatic conditions, with a view to overcoming the inherent problems in extrapolating results from experiments conducted under controlled conditions to the field, are described.

Light

Light influences plant growth and cuticle development. The morphology of plants growing under low light intensity, e.g. in a dense crop, is often different from that of plants growing under high light conditions. A decrease in light intensity was found to increase the ratio of shoots to rhizome nodes in *Elytrigia repens*: this increase may promote the performance of glyphosate because more herbicide can be intercepted per rhizome node.

Light is a requirement for the activity of many herbicides, notably those which affect photosynthesis directly or indirectly by destroying the photosynthetic apparatus. Nevertheless, the activity of the photosynthesis II inhibitors bentazone, ioxynil and bromoxynil, and of some protoporphyrinogen oxidase inhibitors, was found to increase with decreasing light intensity. A plausible explanation is that at high light intensity these non-systemic herbicides tend to limit their own distribution in the leaves because symptoms develop much faster. Furthermore, a high light intensity promotes regrowth of axillary buds which have not intercepted spray directly, and therefore particularly increases the capacity of larger plants to regrow and recover.

Phloem translocation of herbicides is often correlated with the rate of phloem translocation of assimilates, and consequently high light intensity around the time of application can increase the rate of herbicide translocation to the subterranean plant organs. This was found for glyphosate, fluazifop-butyl and sethoxydim on *Elytrigia repens*; however, a high light intensity did not promote the long-term effect of these herbicides. Light intensity had no effect on the long-term effect of glyphosate, whereas the long-term effect of fluazifop-butyl and sethoxydim was inversely related to light intensity. It has been suggested that the inverse correlation was due to a delayed chlorosis at low light intensity allowing more herbicide to be transported to the rhizomes.

Temperature

Pre-spray temperature has a major influence on plant development and can influence herbicide performance. However, relatively few studies have examined the effects of pre-spray temperature and results have not been consistent.

Foliar uptake of herbicides can be regarded as a three-phase process: partitioning from the leaf surface into the cuticle; passive diffusion across the cuticle; and partitioning from the cuticle into the apoplasm (see also Chapter 9). Passive diffusion depends on temperature, among other factors and an increase in temperature would, theoretically, be expected to increase foliar absorption. Many studies have reported an increased uptake with temperature, but others have found no correlation or even a decrease in absorption with increasing temperature.

Similarly to light intensity, an increase in temperature may stimulate photosynthesis and consequently phloem translocation of herbicides. An increased rate of phloem translocation at high temperature has been observed with glyphosate, fluazifop-butyl and sethoxydim on *Elytrigia repens*; however, with the exception of sethoxydim, high temperature did not enhance the long-term effect. An increase in phloem translocation results in a faster removal of herbicide from the leaf tissue and this could be expected to promote foliar absorption by increasing cuticular diffusion and partitioning into the apoplasm.

An increase in temperature increases transpiration and water uptake by the plants. Many studies have shown that uptake of soil-applied herbicides is positively correlated with the rate of transpiration, but some did not reveal any correlation. Differences in the physicochemical properties of herbicides determining herbicide accumulation in the root tissue may explain these differences in results.

As expected from the inconclusive results from the uptake studies, the response in herbicide performance to increasing temperature differs markedly among herbicides. Some herbicides, e.g. the phenoxyalkanoic acids, the hydroxybenzonitriles and bentazone, benefit from high temperatures around the time of spraying, whilst the performance of many of the sulphonylurea herbicides are only slightly affected by temperature. For some non-systemic herbicides high temperature at the time of application, followed by low temperature, was found to optimise performance. A high temperature promotes regrowth from axillary buds, and it seems likely that a better performance following a reduction in temperature some days after spraying can be attributed to a reduced ability of the weed plants to regrow and recover.

In temperate regions frost may occur around the time of herbicide application but very few studies have examined the effect of frost on herbicide performance. The results in the literature suggest that a severe frost which has damaged the foliage has an adverse effect on the activity of foliage-applied herbicides, whereas a light frost often has no effect on herbicide performance or even may enhance activity, as shown for glyphosate on *Elytrigia repens*. In practice frost seems to affect crop tolerance more than weed control, because metabolism in the crop is reduced and frost occurring around the time of application often results in crop damage; examples are the effect of isoproturon in winter cereals and some of the sugar beet herbicides.

Humidity

Humidity primarily influences herbicide performance by affecting foliar uptake. In particular, foliar uptake of water-soluble herbicides is affected by humidity. This is clearly seen when comparing the influence of humidity on the uptake and performance of different formulations of the same herbicide. For example, the activity of the water-soluble sodium salt of ioxynil and the potassium salt of bromoxynil was enhanced by increasing humidity, whereas the activity of the lipophilic octanoate esters of the same two herbicides was unaffected by humidity. Similar results have been found with salt and ester formulations of mecoprop. As humidity is primarily associated with herbicide uptake, it is important that humidity is high during the period of herbicide uptake, i.e. at the time of application and in the short-term post-spraying period. In a study with the water-soluble dinitrophenyl herbicide acifluorfen an increase in humidity from 30 to 95%RH immediately after spraying produced almost the same herbicidal effect as when humidity was kept constantly at 95%RH. In contrast, a corresponding increase in humidity 24 h after spraying had no influence on the performance of acifluorfen. Consequently, those herbicides which produce a greater response at high humidity should be applied during periods of high humidity, and not before or after. Not surprisingly, they generally respond more to the time of day than other herbicides do.

Various mechanisms have been suggested for the enhanced uptake of water-soluble herbicides at high humidity. Firstly, the cuticle is supposed to be more accessible to water-soluble compounds because the hydrophilic pores in the cuticle swell under high humidity conditions. Secondly, at high humidity the spray deposit may retain more water, keeping the herbicide in solution and available for uptake. Thirdly, the water in the spray droplets will evaporate more slowly at high humidity, which may also help to maintain the herbicide in solution and available for uptake for a longer time. Inclusion of adjuvants in the spray solution may reduce the influence of humidity on the performance of water-soluble herbicides (see the section on ‘Adjuvants’ below and in Chapter 9).

Soil moisture

Plants growing under soil moisture stress generally develop smaller leaves and thicker cuticles, deposit more wax and are generally more difficult to control than plants growing under optimum soil moisture conditions. These changes in leaf surface characteristics may reduce retention as well as uptake. Furthermore, moisture-stressed plants gradually close their stomata, leading to a decline in photosynthesis and phloem translocation of assimilates which subsequently reduces herbicide translocation in the phloem. The performance of foliage-applied herbicides is generally reduced when they are applied to moisture-stressed plants and a severe soil moisture deficit affects the performance of foliage-applied herbicides more than any other climatic parameter.

Despite the very pronounced effects of moisture stress on plant morphology and leaf characteristics, plants seem to recover very quickly. Only 24 h after moisture-stressed plants were watered, herbicide efficacy was nearly complete, indicating that it would often be favourable to delay herbicide application if rain is forecast rather than to spray moisture-stressed plants.

Soil-applied herbicides, particularly the ones absorbed primarily via the roots (e.g. the ureas and triazines), may fail totally if the soil is dry around the time of application. This is because the herbicide does not move into the upper centimetres of the soil where most weed seeds germinate and because the roots of weed plants do not explore dry soil. Herbicides absorbed primarily by the shoots (e.g. trifluralin, pendimethalin and propachlor) tend to be less affected by soil moisture deficit, although high soil moisture will also promote the performance of this group of herbicides.

Precipitation

Rain may increase the activity of soil-applied herbicides by dissolving and moving the herbicide into the top few centimetres of soil where most weed seeds germinate. Adequate rain is necessary to maintain a high soil moisture content in the surface layers as this is important for maximising the activity of soil-applied herbicides. In contrast, rain following application of foliage-applied herbicides may wash herbicide off the leaf and result in a substantial loss of activity.

Rainfastness of a foliage-applied herbicide is related to the susceptibility of the deposit to being washed off, rate of uptake, and rain volume and intensity. Deposits of water-soluble herbicides are more susceptible to being washed off than lipophilic herbicides which partition into the surface wax layers. Furthermore, the rate of uptake of water-soluble herbicides is often slow compared with more lipophilic herbicides and it is therefore not surprising that water-soluble herbicides generally are less rainfast than lipophilic herbicides. Diquat and paraquat are notable exceptions which have been attributed to an ion–ion interaction between the cationic herbicides and the anionic cuticle of the leaves. In Table 16.1, the herbicides listed in the group being rainfast within 2 h after application are all lipophilic compounds while the majority of the herbicides in the group requiring more than a 6 h rain-free period are highly water-soluble compounds. Shifting from one formulation of herbicide to another can improve rainfastness substantially, as illustrated by mecoprop. If the climatic conditions in the rain-free period are optimum for herbicide uptake, rainfastness will be improved. The variation of rainfastness between weed species can most probably

Table 16.1 Rain-free period for herbicides to attain maximum activity in semi-field studies using a laboratory rain simulator

0–2 h	2–6 h	> 6 h
Cycloxydim	Chlorsulfuron	Bentazone
Fenoxaprop-p-ethyl	Fluroxypyr	Difenzoquat
Flamprop-m-isopropyl	Metsulfuron	Glufosinate
Fluazifop-p-butyl	Phenmedipham	Glyphosate
Haloxyfop-ethoxyethyl	Triasulfuron	Iodosulfuron
Mecoprop ethylene-glycyldiester	Tribenuron	Mecoprop K-salt
Sethoxydim		Sulfosulfuron
Tralkoxydim		

be attributed to differences in susceptibility of the herbicide deposit to be washed off the different leaf surfaces.

Slight rain, i.e. less than ca 0.5 mm, following application may redissolve and redistribute the herbicide, depositing some of it in areas of facilitated entry such as the leaf sheaths of grasses. Increasing the rain volume increases the amount of herbicide washed off the plants, but after a certain level of rain no further reduction in herbicide activity is observed. In the studies summarised in Table 16.1 increasing rain volume beyond 3–5 mm only marginally reduced herbicide performance further. Hence, the rain volume interval covering the range from no adverse effect to maximum loss of activity seems to be rather narrow (0.5–5 mm of rain). Few studies have examined the effect of rain intensity, i.e. rain duration; it was studied in some of the experiments summarised in Table 16.1 but only minor differences were observed.

Dew may be present when herbicides are applied in early morning or late evening. Little is known about the performance of herbicides applied to wet plants, but the label often recommends application of herbicides only to dry plants. Wet leaf surfaces increase the tendency of droplets to bounce off and some studies have indeed revealed a reduced retention when herbicides were applied to plants with dew, indicating increased droplet bounce-off and/or run-off of herbicide. Despite a reduced retention, herbicide performance is often not reduced and in some cases it is even increased. An increased uptake due to the hydration of the cuticle, to the herbicide being kept in solution for a longer time or to redistribution of some of the herbicide to areas of facilitated uptake may explain the lack of correlation between retention and biological performance. Rewetting of the leaves by dew following herbicide application has been shown both to improve and to reduce herbicide performance. Redissolution and redistribution may explain an enhanced effect, whilst run-off is the most likely cause of a reduced activity.

Alternative approaches to studying the influence of climatic conditions

Another approach to studying the effect of climatic conditions on herbicide performance is to conduct field experiments under contrasting climatic conditions, recording all relevant climatic parameters, and then subsequently to establish correlations between herbicide activity and climatic conditions before, during and after spraying. This approach is costly and rarely produces conclusive data, partly because the inevitable variation of many other factors besides the climatic conditions tends to confound any correlation. A similar approach under controlled conditions is to replace the traditional controlled environment chambers, where climatic parameters can only be examined at fixed levels, with climate simulators, where the natural diurnal fluctuations and interactions can be simulated. Similarly to the ‘field experiment approach’, one compares climate scenarios rather than studying the impact of individual climatic parameters; in contrast to field experiments, however, climatic conditions will be the only parameters varying.

At our institute we have developed climatic simulators where the natural diurnal fluctuations in temperature and humidity can be simulated. Similarly, the natural diurnal fluctuation in light intensity can be mimicked, although our maximum light intensity is significantly lower than maximum natural light intensities. For most of the experiments plants are grown in pots outdoors to resemble field-grown plants and moved to the climate simulators a few days before herbicide application. Plants are removed from the climate simulators and moved outside, i.e. placed under identical climatic conditions, five to seven days after application. The relatively short post-spray period was chosen because weather conditions can only be reliably forecast five to seven days ahead, and hence any influence of climate beyond this period would be difficult to incorporate in dose recommendations. More detailed studies on selected herbicides have generally shown that climatic conditions immediately following application tend to influence herbicide performance more than climatic conditions in the subsequent days, as shown for fluazifop-p-butyl in Fig. 16.4 where the effective dose achieving 90% control (ED_{90}) is shown to differ with temperature conditions.

Many foliage-applied herbicides have been studied in the climate simulators in a varying number of climate scenarios. On basis of the results of these studies so-

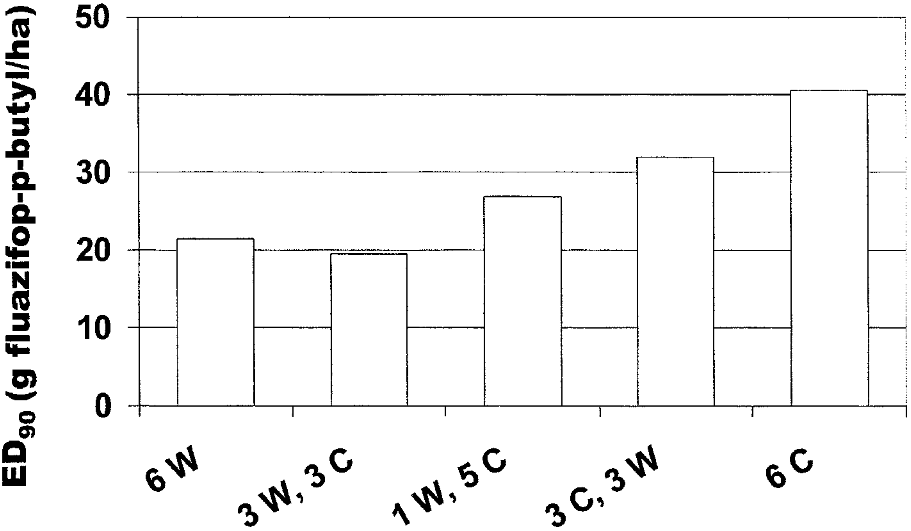

Fig. 16.4 Estimated ED_{90} doses of fluazifop-*p*-butyl applied to barley growing for different numbers of days in a warm (W) (average temperature 20°C) and a cold (C) (average temperature 5°C) climate following spraying (6W: six days in the warm climate; 3W, 3C: three days in the warm followed by three days in the cold climate; 1W, 5C: one day in the warm followed by five days in the cold climate; 3C, 3W: three days in the cold followed by three days in the warm climate; 6C: six days in the cold climate).

called dose adjustment factors have been generated for each herbicide, making it possible to adjust the herbicide dose to the prevailing climatic conditions. Dose adjustment factors vary considerably both for a given herbicide and among herbicides. The dose adjustment factor for bentazone varies from 0.6 to 1.4, whereas the corresponding value for metsulfuron-methyl varies between 0.8 and 1.0. Thus, while the required dose of bentazone may vary by a factor of more than two due to the climatic conditions, the required dose of metsulfuron-methyl is only marginally affected by climate.

The most straightforward way of overcoming the influence of climatic conditions on herbicide performance is to maximise herbicide doses. Label recommendations reflect this and, generally speaking, the recommended dose is often the dose required to maximise herbicidal activity under unfavourable conditions. This approach is no longer acceptable either from an environmental or from a cost-effectiveness point of view, and a more widespread adoption of reduced herbicide doses would re-emphasise the important effects of climatic conditions on herbicide performance.

Application technique

Application technique is a key factor in optimising herbicide performance. The main research focus has been on the selection of nozzle type and size, nozzle pressure and volume rate (Chapter 10). In contrast, relatively few studies have focused on the performance of the sprayer in the field, although an absolute prerequisite for minimising herbicide dose is that the herbicide is uniformly applied, i.e. nozzle output is uniform and boom movements are minimal during spraying.

Nevertheless, application parameters such as nozzle size and volume rate may also significantly influence herbicide performance. Under practical conditions low volume rates are applied using nozzles with a low output producing small droplets, whereas high volume rates are produced using nozzles with a high output producing large droplets. Herbicides like glyphosate and the groups of aryloxyphenoxypropionates and the cyclohexadione oximes generally perform better using low volume rates. The influence of application technique on herbicide activity is probably best documented for glyphosate. Detailed studies have shown that the critical application parameter factor seems to be the concentration of active ingredient and formulation constituents rather than droplet size. However, droplet size may also play a role on difficult-to-wet species such as the grasses.

In contrast, studies on the non-systemic herbicides bentazone and ioxynil + bromoxynil have shown that the herbicidal activity tends to decline when volume rates were below 100 l/ha. It is generally recognised that coverage is crucial to the effect of non-systemic herbicides. Although a low volume rate applied as small droplets, theoretically, can produce the same coverage as a high volume rate applied as large droplets, in practice penetration into the canopy will be lower using small droplets and consequently coverage on the weed plants will be reduced.

With many herbicides no significant differences due to the influence of nozzle size, volume rate and other application parameters on herbicide performance were found. Despite the lack of effect of volume rate on herbicide activity, these herbicides should be applied in low volume rates if permitted by the weather conditions because using low volume rates will increase spraying capacity, i.e. the area sprayed per hour. This means that spraying can be restricted to, or at least primarily be done during, periods of optimum conditions when success with reduced doses is more likely.

Traditionally, herbicides have been applied using conventional flat fan nozzles but this nozzle type has largely been replaced by low-pressure nozzles, also called pre-orifice flat fan nozzles. Conventional flat fan nozzles produce many small droplets and, due to the risk of drift, herbicides often have to be applied in higher volume rates than would otherwise be required to optimise herbicide performance. Low-pressure nozzles produce larger droplets than the corresponding flat fan nozzles when compared at the same nozzle pressure; with low-pressure nozzles lower volume rates can be used with less risk of drift. Only very few studies have reported differences in the performance of conventional flat fan nozzles and the corresponding low-pressure nozzles.

A new type of flat fan nozzles has been introduced, the so-called air inclusion nozzles. These nozzles produce much larger droplets than the equivalent low-pressure nozzles. The droplets contain air inclusions and travel more slowly than droplets of similar size produced by a conventional flat fan or a low-pressure nozzle. The droplets are assumed to break up on contact with the plants and spray retention is assumed to be higher than is indicated by droplet size. These nozzles provide even better drift control than the low-pressure nozzles and are being adopted rapidly by farmers in many countries. Because of the very large droplets it has been speculated that the air inclusion nozzles will not be suitable for pesticide applications to small target plants, i.e. for herbicide applications early in the growing season. Data available from a relatively limited number of experiments indicate that this indeed is the case (Fig. 16.5). Tribenuron applied to *Tripleurospermum inodorum* at the 0- to 2-leaf stage was significantly more active (i.e. had a lower ED_{90}) with a conventional flat fan nozzle than with an air inclusion nozzle, whereas no differences were observed between the conventional flat fan and the low-pressure nozzles. At the two later growth stages no differences were observed between the three nozzle types. Similar results were found with other herbicides and weed species.

The results obtained hitherto suggest that air inclusion nozzles can be used for many herbicide applications without loss of efficacy but that other nozzles should be considered when applying herbicides to small target plants, especially difficult-to-wet weed species. As larger droplet sizes are produced by air inclusion nozzles, spray deposition is assumed to be less affected by wind than that of conventional

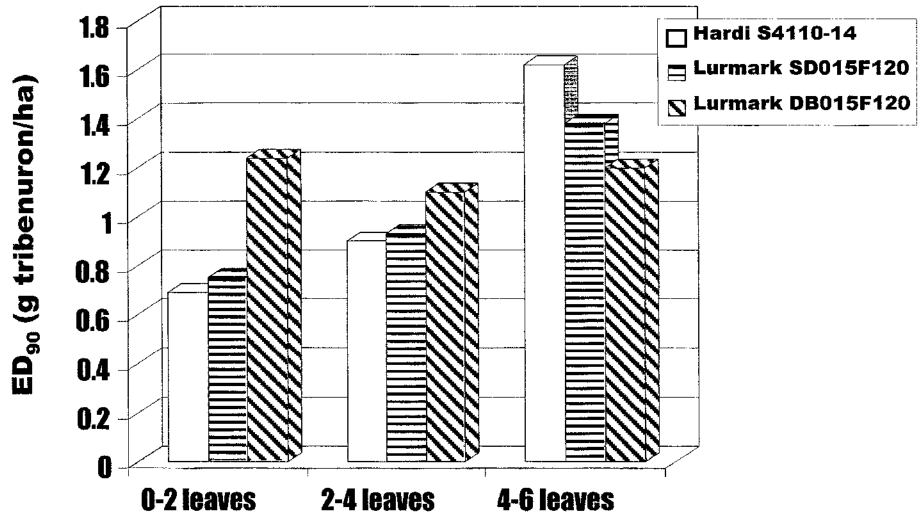

Fig. 16.5 Estimated ED_{90} doses of tribenuron applied to pot-grown *Tripleurospermum inodorum* using a conventional flat fan nozzle (Hardi S4110-14), a low-pressure nozzle (Lurmark SD015F120) and an air inclusion nozzle (Lurmark DB015F120).

flat fan and low-pressure nozzles, i.e. under unfavourable spraying conditions the performance of air inclusion nozzles may surpass that of the other nozzles.

Air-assisted sprayers have also been studied extensively; the overall conclusion has been that the use of these sprayers generally does not result in an improved herbicide performance. However, the use of air assistance considerably reduces drift and permits the use of very low volume rates (30–50 l/ha). This makes it possible to reduce herbicide doses only when spraying under favourable conditions.

Generally, nozzle type and size, nozzle pressure and volume rate have only minor effects on herbicide performance; a few herbicides, most notably glyphosate, are exceptions. Anti-drift nozzles producing much larger droplets, such as the low-pressure and to a certain extent the air inclusion nozzles, can replace the conventional flat fan nozzles without loss of efficacy. Hence, to optimise herbicide dose it is more important that the field sprayer is well maintained and that boom movements are kept at a minimum. If, for example, a high speed results in strong boom movements, the benefits excepted from selecting a proper nozzle and volume rate may easily be lost due to an uneven herbicide distribution in the field, and using reduced herbicide doses may turn out to be a hazardous enterprise.

Water quality is another application variable that may influence herbicide performance and may explain some of the variation in herbicide activity seen across a region. Divalent and trivalent cations particularly have been found to influence herbicide performance. Most notably, glyphosate has been reported to be affected by the presence of cations in the carrier, but other broad-leaved weed herbicides were also found to be susceptible to water quality. Addition of ammonium sulphate may overcome some of the observed antagonism.

Adjuvants

Numerous aspects are taken into consideration when formulating herbicides, e.g. storage stability, ease of mixing with water and operator exposure. However, probably the single most important aspect is to optimise herbicide activity. Adjuvants play a vital role in formulations and are the most important constituents of the formulation in relation to biological activity. In some cases it is not technically possible to build adjuvants into the formulation. Alternatively, they may only be recommended for specific applications, and with these herbicides the chemical companies recommend the user to include a tank adjuvant in the spray solution. The most commonly used adjuvants in herbicide formulations are the surfactants.

The choice of formulation is always a compromise to meet the very different conditions of applications, and an optimum formulation of a herbicide does not exist. This suggests that there might be room for improvement of the commercial formulations under certain conditions; the array of tank adjuvants available on the market in most countries confirms this, although the benefits of adding tank adjuvants to ready-to-use herbicide formulations are often not well documented. Adjuvants should be used with care, particularly with herbicides, because they may reduce crop tolerance. The purpose of this section is not to review the mechanisms of adjuvant action but to give examples of how the use of tank adjuvants may improve herbicide performance under adverse application conditions by overcoming impediments such as those imposed by climatic conditions.

There are numerous examples of how addition of tank adjuvants may improve the rainfastness of herbicides despite inclusion of adjuvants in the formulation. The most pronounced effects have been found with poorly rainfast water-soluble herbicides such as glyphosate, glufosinate, bentazone, salt formulations of the phenoxyalkanoic acid herbicides and the sulphonylurea herbicides. There has been much interest in the use of organosilicone surfactants as enhancers of rainfastness. These surfactants promote stomatal infiltration due to an exceptionally low surface tension. Herbicide entering the stomatal cavity becomes fully rainfast shortly after application. Whereas most broad-leaved weed species have the majority of their stomata on the abaxial (lower) leaf surface, grasses generally have stomata on both the adaxial and abaxial leaf surfaces and consequently the most promising results obtained with organosilicone surfactants have been on grasses. Besides specificity for weed species, organosilicone surfactants also have a pronounced specificity for herbicide formulations.

Humidity primarily affects herbicide uptake and it could therefore be speculated that adjuvants could overcome the adverse effects of low humidity by enhancing uptake rate or through their hygroscopic properties. Indeed, a reduced influence of humidity on herbicide performance has been found with a number of water-soluble herbicides, e.g. glyphosate, glufosinate and bentazone. The results shown in Fig. 16.6 originate from research in our climate simulators. At high humidity addition of a mixture of a non-ionic surfactant and ammonium sulphate did not improve glyphosate activity however at low humidity inclusion of the two adjuvants reduced the poor performance and resulted in an effect comparable to the effect at high humidity. Hence, addition of the adjuvants eliminated the adverse effect of low humidity.

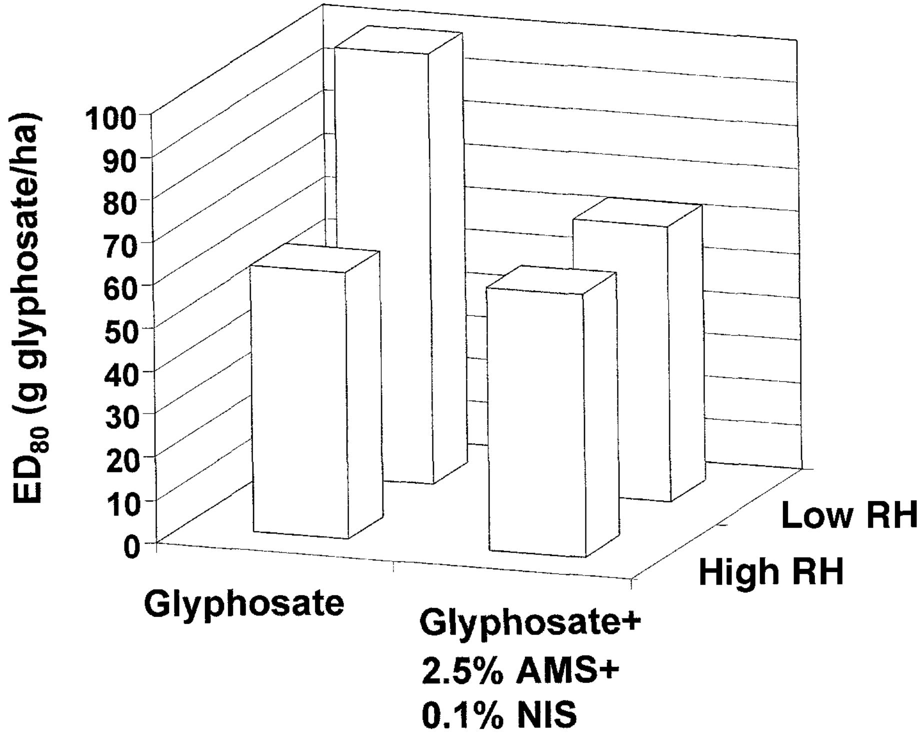

Fig. 16.6 Estimated ED_{80} doses of glyphosate as Roundup applied, alone or in mixture with an adjuvant, to barley growing at contrasting humidity (AMS: ammonium sulphate; NIS: non-ionic surfactant; RH: relative humidity).

Some herbicides perform better at lower than at higher volume rates (see section on 'Application technique'). If this is attributed to a sub-optimum concentration of adjuvant in the spray solution the problem might be overcome by including a tank adjuvant. A sub-optimum concentration of adjuvant could be the result of using higher than recommended volume rates but it could also be caused by using reduced doses at the recommended volume rate. Haloxyfop-ethoxyethyl is an example of a herbicide performing better at a low rather than at a high volume rate. Furthermore haloxyfop-ethoxyethyl is recommended for use at very different doses, depending on the weed problem in question. Addition of a non-ionic surfactant improved the performance of this herbicide much more at the high volume rate (i.e. at a low concentration of the built-in adjuvants) than at the lower volume rate (Fig 16.7). Performance with adjuvant was more consistent across volume rates.

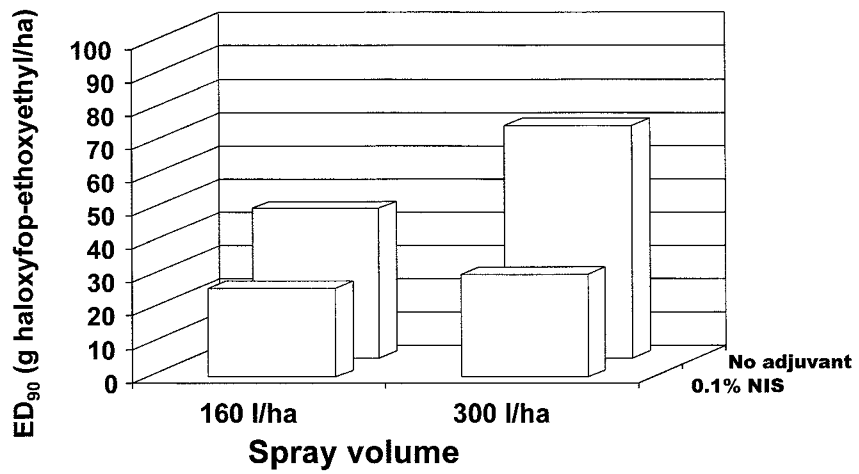

Fig. 16.7 Estimated ED_{90} doses of haloxyfop-ethoxyethyl applied, alone or in mixture with a non-ionic surfactant, to barley at two volume rates (NIS: non-ionic surfactant).

Partly as a response to these results, the producer now recommends addition of a tank adjuvant at doses lower than 40% of the maximum recommended dose. Similar recommendations are in place for chemically related herbicides such as propaquizafop.

The examples given in this section clearly show that the use of tank adjuvants may fully or partly overcome the impediments imposed by adverse application conditions. Often reduced herbicide doses are avoided because of the risk of an increased variability in performance; however, proper use of adjuvants may eliminate or at least minimise this risk and thereby improve the reliability of reduced herbicide doses.

Herbicide mixtures

Most herbicides can control certain weed species at doses well below the recommended dose while other weed species require higher doses and yet others are not controlled even at the recommended dose (see Fig. 16.1). Farmers are well aware of this and in order to optimise weed control and minimise the costs of controlling a mixed weed flora, the use of herbicide mixtures has become the rule rather than the exception in many countries.

The performance of one herbicide is often impaired by the presence of other herbicides in the spray solution (see also Chapter 9). Numerous examples are documented in the literature, e.g. those of the aryloxyphenoxypropionates, graminicides and various broad-leaved weed herbicides such as phenoxyalkanoic acids, triazines, bentazone and glyphosate. If one herbicide impairs the performance of another it is called 'antagonism'. Antagonism can have several causes, which can be classified as biochemical, competitive, physiological or chemical. Biochemical antagonism occurs if one herbicide reduces the uptake and/or translocation or increases metabolism of the other herbicide. The antagonism of aryloxyphenoxypropionates by the phenoxyalkanoic acids is an example of biochemical antagonism. An example of intended biochemical antagonism is the use of the safener mefenpyr-diethyl in combination with the herbicides fenoxaprop-p and iodosulfuron. The safener increases the rate of metabolism of the herbicides in the crop, allowing for their selective use in cereals. Competitive antagonism occurs if the herbicides compete for the same binding site, whilst physiological antagonism may occur if two herbicides have opposite physiological effects. An example of the latter is mixture of the wild oat herbicide flamprop-p (an anti-auxin) with a phenoxyalkanoic herbicide (which mimics the effect of auxins). Lastly, antagonism may be chemical, i.e. one herbicide inactivates another herbicide because of a chemical reaction in the spray solution. An example is mixture of the dichloride salt of paraquat and the dimethylamine salt of MCPA leading to the formation of two compounds with less biological activity than the parent compounds. A similar mechanism is responsible for the antagonistic effect of calcium, magnesium and other cations on the activity of glyphosate.

One herbicide may also promote the performance of another herbicide; this is called 'synergism'. Synergism can often be attributed to an increased uptake and/or translocation, or a reduced metabolism. Mixtures of the sugar beet herbicides phenmedipham and ethofumesate have been found to be synergistic. Often synergism is caused by the formulation constituents of one of the herbicides rather than by interaction of the active ingredients. Hence, fungicides and insecticides may also synergise the activity of herbicides, e.g. when a formulation of a water-soluble herbicide with a low content of adjuvant is mixed with a fungicide or insecticide formulated as an emulsifiable concentrate with a high content of solvents and adjuvants. There are also examples of synergism between herbicides and insecticides caused by reduction in herbicide metabolism by the insecticide.

Generally synergism between herbicides seems to be less common than antagonism, although synergism is often claimed in patents. One reason is that the terminology used in the literature to describe the performance of herbicide mixtures has been anything but stringent and this has caused much confusion. A prerequisite for detecting antagonism or synergism is that a scientifically sound joint-action reference model is used to predict the expected effect of a herbicide mixture. Various joint-action reference models have been applied in the literature, but those most frequently applied can be grouped into additive dose models (ADM) and multiplicative survival models (MSM). The ADM (also called the isobole method) assumes additivity of doses, i.e. one herbicide can be replaced, wholly or in part, by another herbicide at equivalent doses; the MSM assumes that the expected efficacy of a herbicide mixture can be calculated by multiplying percentage survivals of the individual herbicides. Consequently, a fundamental difference between the ADM and the MSM is that the ADM considers dose rates while the MSM considers effects. It has been claimed that the ADM is a reasonable reference model for mixtures of herbicides with similar modes of action whereas the MSM is more applicable for mixtures of herbicides with dissimilar modes of action; however, this argument has been disputed in the medical and pharmacological literature, where the ADM concept has been postulated to be the proper method to analyse also the combined effects of drugs with dissimilar modes of action.

It is not the scope of this chapter to engage in a discussion of the pros and cons of the two joint-action models beyond stressing two points: (1) the MSM assumes that herbicides act independently and sequentially, i.e. neither herbicide influences the effect of the other(s), which seems to be an oversimplification even for mixtures of herbicides with entirely different modes of action; and (2) as the ADM assumes that one herbicide can replace another herbicide at an equipotent dose it is possible to design mixtures producing a given effect if a herbicide mixture follows the ADM and the doses required to produce that effect of the herbicides applied alone are known. In contrast to the MSM, adoption of the ADM makes it possible to optimise the composition of herbicide mixtures and therefore the ADM is of more practical interest than the MSM.

The application of the principles of the ADM to optimise the composition and doses of herbicide mixtures is illustrated in Fig. 16.8(a) for a hypothetical mixture of a herbicide A and a herbicide B on three weed species. The doses required of the two herbicides to produce 90% effect on the three weed species and the costs per gramme of each herbicide are shown in Table 16.2. According to the ADM any mixture along the isobole connecting the points on the axes which indicate the doses required of the two herbicides to obtain a 90% effect when applied alone will also produce a 90% effect. An isobole exists for each weed species and any mixture along the outer isobole, illustrated by the full line, will produce at least a 90% effect on all three weed species. For example, mixtures on the upper section of the outer isobole produce a 90% effect on weed species 3 and more than 90% effect on weed species 1 and 2. Mixtures on the middle part of the outer isobole produce 90% effect on weed species 2 but more than 90% on weed species 1 and 3. Finally, mixtures on the lower part of the outer isobole produce 90% effect on weed species 1 and more than 90% on weed species 2 and 3. The mixtures represented by the interceptions of two isoboles produce 90% effect on the

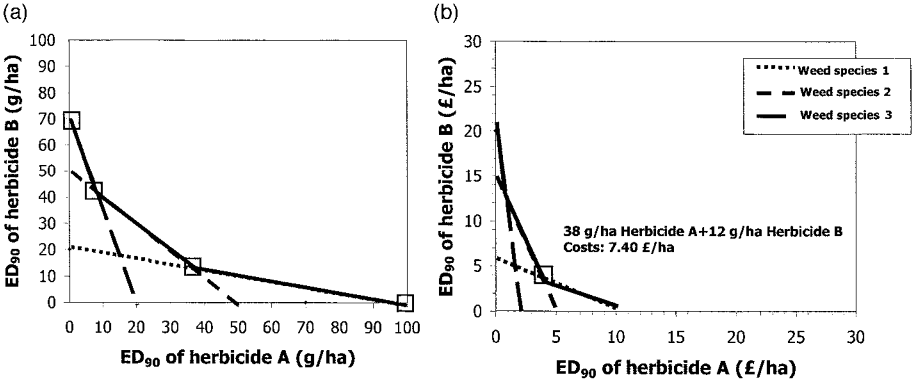

Fig. 16.8 Illustration of the concept of the ADM for two herbicides and three weed species, expressing doses as g/ha (a) and £/ha (b) (see text and Table 16.2 for further details).

two weed species that the isoboles represent but more than 90% effect on the third weed species.

The fact that the outer isobole is not a straight line means that the mixture represented by the intercepts of the isoboles or the intercepts of the isoboles and the axes is the mixture requiring the lowest total dose of herbicide to control all three weed species at an effect level of at least 90%. From a practical point of view it is, however, of little interest to minimise the total dose of herbicide whereas it is of paramount interest to be able to design the herbicide mixture representing the lowest possible cost of treatment. This can easily be done by expressing the doses as £/ha rather than g/ha by multiplying the dose in g/ha by the cost of 1 g of herbicide. This is illustrated in Fig. 16.8(b): in this example herbicide costs were minimised by using a mixture consisting of 38 g/ha of herbicide A and 12 g/ha of herbicide B.

Isoboles can be constructed for any effect level and herbicide mixtures can be optimised assuming different effect levels for different weed species. If a herbicide only controls one of the weed species the isobole is parallel to either the *x*-axis or the *y*-axis. The ADM concept can be extended to mixtures consisting of any number of herbicides but it is only possible to illustrate two- and three-way mixtures on a single two-dimensional diagram.

Table 16.2 ED_{90} doses and costs of the herbicides A and B

	Ed_{90} dose (g/ha)			Cost (£/g)
	Weed species 1	Weed species 2	Weed species 3	
Herbicide A	100	50	20	0.1
Herbicide B	20	50	70	0.2

One of the advantages of applying the ADM to optimise herbicide mixtures is that it makes it possible to exploit fully the strong points of a herbicide, be it a high biological activity on specific weeds or a low cost.

Crop competitiveness

Crops vary considerably in their ability to suppress weeds and even among crop cultivars pronounced differences can be seen. In more competitive crop cultivars total weed biomass is lower than in less competitive cultivars, and a lower effect is required to reduce weed biomass to a given level. Hence, in more competitive cultivars lower herbicide doses are required than in less competitive cultivars. Among the growth parameters registered in the variety testing of cereal cultivars, crop competitiveness has been shown to correlate closely with straw length. Besides the crop cultivar, the time of sowing and the crop seed density also affect crop competitiveness and hence herbicide performance.

Conclusions

Most research on the influence of biotic and physicochemical factors on herbicide performance hitherto has been qualitative, i.e. the researchers have merely focused on whether the observed differences were statistically significant or not. Such information is valuable because it allows for a ranking of the individual factors and forms the basis for the label recommendations on optimum conditions of application; however, it does not provide any indication of how much the doses can be reduced under optimum conditions. Increased environmental and cost pressures are forcing farmers to consider more advanced approaches to adjust herbicide choice and dose to the prevailing conditions in the field. One such approach is the concept of factor-adjusted doses applied in the Danish decision-support system ‘PC Plant Protection’ where dose adjustment factors are generated for various parameters.

Log–logistic dose response curves have been generated on the basis of data from efficacy testing required by Danish legislation. If it can be assumed that the dose response curves for a particular herbicide on different weed species are parallel, then the influence of weed growth stage can be described as a horizontal or parallel displacement. Parallel dose response curves imply that the ratio of herbicide doses giving similar effects is constant at all response levels, and the ratio expresses how much the herbicide has to be increased to maintain activity or can be reduced without loss of activity. The effect of climate on herbicide performance could not be expressed as a horizontal displacement; instead dose adjustment factors were calculated on the basis of the observed differences in the 70–95% control range. The effect of crop competitiveness on herbicide performance is an indirect rather than a direct effect because the crop does not influence herbicide activity *per se* but it reduces weed biomass. Hence, the effect of a competitive cultivar is described as a reduction in the initial weed biomass, which serves as a point of reference for calculating the dose required to reduce weed biomass to a given level.

The concept of factor-adjusted doses has been shown to provide a reasonable basis for assessing the influence of weed species, weed growth stage and climatic conditions on herbicide performance in a decision-support system context. Numerous validations have shown that herbicide doses on average have been reduced by 50% compared with the recommended doses. The recent implementation of a herbicide mixture module based on the ADM concept has resulted in further reductions in the doses recommended by 'PC Plant Protection'.

In contrast to most decision-making on diseases and pests, any decision-making on weed control should also consider the long-term effects, i.e. weed-seed return to the soil. Information on seed production of broad-leaved weed species following the use of reduced herbicide doses is becoming more abundant and most research has concluded that seed production is linearly related to biomass production and therefore seed production can be estimated fairly well based on the available information on herbicide effects on biomass production, and subsequently incorporated in the decision-making process.

Optimising herbicide performance should be considered as one element in an integrated weed management strategy (see Chapter 14) but because it is a very straightforward and relatively simple way of reducing herbicide inputs compared with changing cultivation practices or crop rotation, and because also the costs of weed control are reduced and profitability is often improved, it deserves greater attention.

Chapter 17
Biological Control of Weeds

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Introduction

Biological control of weeds first appeared in the 6th edition of the *Weed Control Handbook* in 1977 when it was restricted to a short paragraph in the chapter on aquatic weed control. This noted that the potential to use Chinese grass carp to control weeds in British waters was being investigated by the Ministry of Agriculture.

By the next edition, in 1982, the subject warranted a whole page in the chapter on weed biology. Most of this page still dealt with the grass carp and the rest merely noted that ‘the possibility of utilising organisms that attack weed species to achieve biological control is currently receiving much attention’. The overall conclusion was that biological control was feasible only in a minority of situations.

Since then the agricultural scene in Europe has changed significantly. The present emphasis on sustainable systems, organic production and environmental conservation has fuelled a groundswell of antipathy towards chemical pesticides. Consequently, increased attention has been paid to the potential to employ alternative weed control strategies, including biological methods. Ironically, those pressure groups that have campaigned for so long against chemicals now seem to be turning their attention to biological control agents. They seem determined to establish them in the public eye as biological warfare agents, which will mutate and decimate crops and desirable non-crop species, or even infect man and animals. There are also claims that the organisms being considered for use as biological control agents are genetically engineered to be some sort of ‘Frankenmonster’. It is to be hoped that this irresponsible attitude will not prevail and an exhaustive, fully objective, scientific investigation of the subject will be allowed to develop unhindered.

Certainly, such an investigation is absolutely necessary. Although the research since 1950 has proved that biological control systems can work spectacularly well, it has also shown, especially in the case of microbial herbicides, that they can fail just as spectacularly.

Several forms of biological control have been described and variously defined.

For simplicity and clarity, this chapter will confine itself to the two principal strategies, classical biological control and microbial herbicides.

Classical biological control

This is a strategy based on the observation that species introduced to a new region, without their normal pests and pathogens, invariably flourish and can easily become dominant. In classical biological control, host-specific natural enemies are taken from the native range of a weed and established in its introduced range, where they reduce the weed population to a level where it is no longer problematic. This control method cannot, however, eradicate the weed.

The strategy requires the agent to establish, reproduce and spread in the area of introduction. It is therefore a relatively slow means of controlling the weed target and is principally suited to stable ecosystems. This limits its application in agriculture and horticulture to 'permanent' crops, such as grassland or fruit, shrub and tree production. Nevertheless, in the USA and Australia it has been applied with some success to the control of *Chondrilla juncea* (skeleton weed) in cereals, but this is the exception rather than the rule. The strategy is also applicable to semi-natural habitats on the farm, including water courses and drainage channels, and in forestry.

There are many examples of the successful application of this strategy, especially against European weeds exported to, and established in, for example, the USA and Australia. The well-known system of using Chinese grass carp to control aquatic weeds, which could be described as a quasi-classical strategy even though the fish do not breed in UK conditions, has been applied quite widely in British enclosed waters. However, so far there has been no application of the classical biological control strategy against weeds in British or European agriculture. Some recent research which has focused on this approach under the auspices of a European Community Co-operation in Science and Technology (COST) project suggests that the prospects are good, at least in some areas such as fruit and vegetable production.

In the 1980s research into the biological control of bracken (*Pteridium aquilinum*), using moths from South Africa, indicated good potential for successful control. The organisms, larvae of species of noctuid and pyralid moths, bore into the bracken pinnae and then into the rachis, causing considerable damage and allowing secondary invasion by pathogens. The biological and technological problems associated with rearing the moths in quarantine conditions were successfully overcome and small-scale studies in containment indicated that successful control was possible and that the moths appeared to be bracken-specific. However, a large number of political, legislative, environmental and socio-economic problems have so far prevented the release of the organisms, and biological control of bracken remains potential, not actual. As herbicides are not a realistic proposition for bracken control on environmental and economic grounds, bracken continues to spread at 1–3% per annum, further reducing production from what are, generally, already disadvantaged upland areas.

This research was unusual in that it was one of only a few attempts to apply classical biological control to a native species. The lack of attention to native species is a reflection of the importance of introduced species as weeds, but may also arise from a widely held, but ill-founded, belief that the strategy will only work for alien species.

Microbial herbicides

In contrast to classical biological control, in which the agents become permanent members of the biota in the area into which they are introduced, there is an alternative strategy. This strategy exploits transient epiphytotic populations of an agent. As the agents are, normally, plant pathogenic micro-organisms, the strategy has become known as the microbial herbicide strategy (among other names). In the many instances where the control agent is a plant pathogenic fungus, the term 'mycoherbicide' is widely used. In this chapter the more general term, 'microbial herbicides', will be used.

The use of plant pathogens to control weeds is well established, research first being reported in 1890. Since the 1950s, however, research has become intensive and focused. Rewards came quite early with the deployment in the 1960s of the wilt fungus *Acremonium diospyri* to control persimmon trees (*Diospyros virginiana*) in the Oklahoma rangelands of the USA. The trees were inoculated with the fungus by hand-wounding the trees with axes and painting spores into the wounds. A similar method was used to control kolomona weed (*Cassia surratensis*) in Hawaii using a *Cephalosporium* sp.

The modern concept of a microbial herbicide (mycoherbicide) was developed in the early 1960s when it was demonstrated that a native plant pathogenic fungus could be made effective as a control agent by applying a sufficiently large dose to a susceptible growth stage of the target weed. In effect, a massive epidemic of disease was induced in the weed population. This effectively overcame those environmental and biological factors that normally constrain such pathogens and prevent them from killing their host.

Candidate microbial herbicides must be host-specific, of course, but they must also be genetically stable, capable of economic mass production of durable inoculum and capable of infecting and killing the weed target in the wide range of environments in which it is found. The organism is applied annually or, rarely, more often, before or soon after weed emergence and in a formulation that both allows it to be applied with standard application equipment and to withstand periods of unfavourable climatic conditions. In this sense, the microbial herbicide strategy is clearly technology-based, whereas the classical strategy is ecology-based. Furthermore, microbial herbicides generally must be commercial products, whereas classical agents require 'public-good' finance.

The nature of the production, formulation and application of microbial herbicides identifies them as analogous to pesticides. As such they are subject to national and international regulations more closely related to those governing pesticides rather than those designed to control the release and monitoring of classical agents. These regulations also demand that the product conforms to specified safety and efficacy criteria and is standardised, at least with respect to each batch of product.

The first microbial herbicide, registered with the US EPA (Environmental Protection Agency) in 1981, was Devine™. This is a preparation of *Phytophthora palmivora* that is highly effective for the control of milkweed vine (*Morrenia odorata*) in citrus groves in Florida. In many ways, this product is atypical as a microbial herbicide. It does not have durable inoculum and must, therefore, be prepared specifically for identified customers just before it is needed. It is then handled like fresh milk until use, being stored in a refrigerator. Further, it has proved to be somewhat stable in the environment after application. Rather than dying out after controlling its target, it survives in the soil in sufficient quantity to infect and control the weed over a period of some years, so acting more like a classical control agent. This commercial disadvantage is, naturally, welcomed by the growers.

The second microbial herbicide to be registered, in 1982 and also in America, was Collego™. This product contains the spores of *Colletotrichum gloeosporioides* f. sp. *aeschynomene*, a pathogenic fungus specific to a leguminous weed (Northern joint vetch, *Aeschynomene virginica*) of rice and soybean in the southern states of the USA. To some degree it has become the yardstick by which all potential microbial herbicides are judged. Whilst it is undoubtedly successful, its role as a model is, perhaps, unfortunate. Both of the crops in which it is used are 'wet' crops. Rice is grown in the paddy system and soybeans are heavily irrigated. In both cases, therefore, the control agent is protected from the damaging effects of post-application desiccation which are imposed on most other microbial herbicides. Thus, the rapid transition from laboratory to field that was achieved with Collego™ has set expectations for other biological control products that are difficult, if not impossible, to achieve. Nonetheless, a considerable research effort has been put into finding, and attempting to develop, further microbial herbicides and some products have appeared on the market. Notably, Camperico™, a formulation containing the pathogenic bacterium *Xanthomonas campestris*, has been approved for control of annual meadow grass (*Poa annua*) on golf courses in Japan. As this organism can only infect its target through wounds, it is applied to cut grass immediately behind the mower. A formulation of *Colletotrichum gloeosporioides* f. sp. *cuscuta*, known as Luboa II, is used in China to control dodder (*Cuscuta* spp.). Other plant pathogens developed as products in the USA (CAAST™ and Biomal™) have failed to appear on the market for commercial reasons, possibly arising from poor reliability.

Research continues worldwide to try and exploit the possibility of microbial herbicide use in agriculture. Thus, in 1991 projects on 68 weed species in 16 countries and 44 locations, 18 of which are in the USA, could be identified. There is no evidence that this effort has since been significantly reduced. In Europe, research has been relatively limited. The principal projects concern control of bracken (*Pteridium aquilinum*) by *Ascochyta pteridis*, fat-hen (*Chenopodium album*) by *Ascochyta caulina*, field pansy (*Viola arvensis*) by *Mycocentrospora acerina*, pigweed (*Amaranthus retroflexus*) by *Alternaria* sp. and brome grass (*Bromus* spp.) by *Dreschlera* sp. With one exception all these plant pathogens were identified as having useful potential as microbial herbicides. The exception was that for fat-hen control, where the fungus appeared to have lost virulence since it was originally isolated and, thus, only achieved poor levels of control in field trials.

Integration of biological control into weed management strategies

A major feature of the European research in the 1990s was the formation of a collaborative programme, under the auspices of the EC COST programme. This focused on four major weeds of European agriculture, fat-hen, bindweeds (*Convolvulus arvensis* and *Calystegia sepium*), pigweed and groundsel (*Senecio arvensis*) and addressed a range of biological control agents and strategies. Essentially the work identified potential in all the systems studied but also identified several serious problems remaining to be solved before any system could be used in practice. A common, and important, theme of the project was the need to integrate the systems into sustainable agricultural practice. Such integration is essential, if only because agriculture will continue to use chemical pesticides, including fungicides, for the foreseeable future. Thus, any fungus or other organism used as a biological control agent must be resistant to, or protected from, the inherent adverse effects this usage can cause. On the other hand, it is well established that several herbicides, used at very low doses, can synergise the effects of microbial herbicides; this synergism may be open to exploitation in an integrated system.

Another aspect that needs to be considered, in the context of developing sustainable weed control strategies, is whether it is necessary to kill the weed target. Several researchers have shown that sub-lethal infection of a weed can eliminate its competitive effects on the associated crop. As the infected weeds have reduced vigour, they are likely to produce less seed of lower viability, so reducing the problem of seed banks in the soil being increased. This is an exciting area that is worthy of detailed research at the earliest opportunity. Such an approach to weed management would leave the weed populations to support their normally associated insect fauna and so increase the biodiversity of the arable farming system. Admittedly, it may be difficult to persuade a farmer that he should abandon firmly held tenets such as ‘the only good weed is a dead weed’ and ‘the only good crop is a weed-free crop’. Nonetheless, the potential for weedy but productive crops to enhance the arable environment is clear enough to warrant closer examination.

The 'potential' of microbial herbicides has been referred to frequently above. Sadly, despite much sound research, 'potential' is all that there is. Apart from the few agents mentioned earlier, there has been no success in producing practical products on the market. Critics will say that this simply shows that plant pathogenic organisms are not suitable for development as biological control agents. Undoubtedly, this is true for some of the organisms that have been selected for study. However, examination of the published literature reveals other reasons. Too many projects have been concerned solely with discovering and culturing organisms that are specific to certain weed species, the so-called 'stamp collecting' approach. In addition, many of the weed targets chosen are too parochial to offer a market size that warrants the considerable research investment necessary to develop a product. Finally, all too little attention has been paid to the formulation and application of the agents. Even if all the published effort were appropriate, the total investment in microbial herbicide research since the 1950s is a very small fraction of that put into herbicide R&D in one year. Thus, it could be concluded that microbial herbicide development, to date, appears to have been comparatively productive.

Formulation and application of microbial herbicides

Of the reasons given above for restricted progress in microbial herbicides, the lack of attention to formulation is particularly important. As mentioned earlier, the first and 'model' microbial herbicide, Collego™, has an unfair advantage in being used in 'wet crops'. In general, the post-application period in most crops in Europe is going to be quite dry. The incidence of dew periods that are long enough to allow fungal spores placed on leaf surfaces to germinate, grow, infect and establish disease is low. Usually exposure to free water or high humidity for more than 6 h, sometimes for as long as 24–48 h, is required to achieve this. Dew periods of more than 4–6 h are rare in Britain in the period when applications are made. Similarly, the sort of rain that would provide wetness without washing spores off the leaf is relatively infrequent and unpredictable. Thus, the spores need careful formulation to protect them from desiccation and to ensure good distribution and retention on the target. Good progress has been made in this direction but much remains to be achieved. One drawback seems to be that it is unlikely that only a few formulations will be required for the range of micro-organisms to be developed as microbial herbicides. Each micro-organism will probably require a tailor-made formulation that reflects its particular susceptibilities to exogenous chemicals and to climatic variables. This imposes a notable economic disadvantage on microbial herbicide development.

It has always been assumed that the spraying systems to be used for microbial herbicides should be the same as those used for other crop protection products.

Should special new sprayers be required to deliver microbials, the economic penalty would be enough to preclude their uptake by the farmer. However, research by the author's group has shown that conventional sprayers fitted with simple hydraulic nozzles may not permit adequate distribution and retention of the agent on the target weed. In particular, the losses of spores between emergence from the nozzle and impact on the target can be very high. Similar losses from conventional sprays of highly active chemical herbicides are more easily tolerated, as the small amount deposited on the plant is still effective. In contrast, reduction in spore deposition appears to lead rapidly to almost complete loss of efficacy. This problem seems to be related in part to the large numbers of small droplets ($< 150\,\mu m$ VMD (volume median diameter)) which are produced by simple hydraulic nozzles and which frequently do not carry spores. The situation is improved by using twin-fluid nozzles and, especially, spinning disc applicators, in which the drop size spectrum can be more closely controlled. This research has also suggested that angling the spray at 45°, and directing it forwards in relation to the direction in which the sprayer is travelling, also improve deposition on the target. A similar improvement may be obtained using drop-leg sprayers in which the nozzles are held horizontally at the same level as the weed seedlings. In particular, deposition on the stems and hypocotyls is improved. These are the most important sites in which to establish infections as leaf infection can be overcome by the plant, which sheds the dead leaves and later produces new ones. Similarly, if only apical meristems are killed by the microbial herbicide, lateral meristems will grow and produce a bushier weed with several side-shoots. Thus, death of apical meristems and leaves, especially in vigorous weeds, may only check weed growth for a short time; thereafter, the weed may be more competitive than it would otherwise have been. Clearly, if microbial herbicides are to contribute to weed management in field crops, significant attention must be paid to the development of optimal spraying systems that are fully integrated with other aspects of the husbandry of the crop concerned.

An alternative formulation/application system that has received attention recently, especially in the USA, is that of granular application. Whilst the use of solid formulations is not new, recent work on 'Pesta' granules, formed from a gluten base, suggests that they have significant advantages of ease of mass production, stability and efficacy. Further, they are placed in an environment which is buffered against the wide fluctuations in environmental conditions that might be experienced by fungi placed on leaf surfaces. However, the introduction of nutrient-based granules into soil can stimulate mass development of populations of soil fungi and other micro-organisms which, in turn, stimulate populations of invertebrates, such as enchytrid worms and nematodes. The net result can be inhibition of the control agent and destruction and dispersion of the granule. In practical terms, the use of granules can involve relatively high application rates, especially if the fungus they contain can grow only a short distance into the surrounding soil. In such a case, the granules must be applied at such a high rate that the intergranule distance is small enough to ensure that the fungus encounters its target weed. This may be economically unacceptable. Nonetheless, granule systems may have a role in applications within the rows of widely spaced, high-value crops or where suitable fungi, with a long survival time in soil, can be delivered using the seed drill when the crop is sown.

Future developments in biological control of weeds

According to a recent comprehensive review of microbial pesticide development (Copping, 1996):

> 'Early research papers investigating potential new organisms usually spoke airily of promising results, often like love affairs between scientists and their science. Further investigations in the harsh reality of field use for pest and disease control made it abundantly obvious that progress in attempts to better the natural performance of the organisms required eventual commercialisation of well-formulated products.'

Nowhere is this truer than in the area of microbial herbicide development.

It is no doubt true that microbial herbicides can contribute to crop protection in European agriculture, just as they do in the USA. However, in order to make that contribution, there must be a clearer recognition by the researchers that there must be a viable market for their organism. Thus, the weed target must be chosen with great care, recognising that the selectivity that gives the microbial herbicide an environmental advantage also confers a major economic penalty. The organism must be subject to a ruthless assessment of its suitability. Is it sufficiently robust to withstand long-term storage without loss of viability? Can its spores be produced easily and cheaply? It is simply not acceptable to work on an organism because it 'works in the laboratory'.

Perhaps because the approach to microbial herbicide research has not been sufficiently stringent in the past, there is now little enthusiasm on the part of either public or private funding agencies to support the necessary research. Indeed, in 2001, the UK had no funded research projects on microbial herbicides.

Basic research is needed to extend our understanding of the ecology of organisms in relation to their target weeds and the natural safeguards that have evolved in order to prevent extinction of the hosts. Do these organisms, growing on living weeds in a natural environment, possess different characteristics and behaviour from the cultures that are mass-produced and formulated as commercial products? Can we control and exploit any relationships between nutrition during spore formation, storage capacity and virulence and efficacy in the field? Answers to such questions are essential before microbial herbicides can be developed and exploited properly.

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Chapter 18
Weed Management Strategies for Winter Cereals

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Introduction

Weeds need managing for a number of reasons: to protect crop yield, to protect crop quality, to ensure ease of harvest, to prevent problems in following crops, to reduce spread of pests and diseases, and last, but certainly not least, pride.

Weed management options

Weed management should be planned across a whole rotation. This alters the weed pressure and allows a wide range of weed control options to be employed, including cultural options, herbicide use and mechanical weeding (Table 18.1).

The changing need for weed control

The needs of weed management are changing. At the end of the 20th century this meant high levels of control, often spraying if weeds were seen and with the choice of a wide range of herbicide options. However, in the 21st century weed 'management' is more relevant than 'control'. The need for a more cost-conscious approach which includes awareness of biodiversity means that consideration now needs to be given to how many weeds can be left, and means a greater desire for weed management strategies that are more selective. It is also likely that herbicide choice will become more restricted, especially in non-cereal crops, and herbicide resistance will be of increasing importance.

How many weeds can I leave?

Although some weeds are very competitive with the crop, many species do not need controlling. Weeds are also important components of biodiversity and are valuable in providing food for birds, either directly, or as hosts for insects which

Table 18.1 Weed management options

Option	Strengths	Weaknesses
Rotation	*Very large impact on weed numbers and species present*	
	Using both winter and spring sowing dates reduces the dominance of individual weed species. Some weeds easier to control in certain crops. Allows wider range of herbicide groups.	Range of economically viable crops may be restricting. May be restricted by previous herbicide use.
Cultivation	*Large impact on weed numbers and species present*	
Ploughing	Buries weed seeds, especially grasses. Reduces risk of herbicide resistance. Reduces herbicide residues. Removes compaction. Favours some weed species (e.g. *Polygonum* spp., fat-hen, scarlet pimpernel).	Often slow. Can be more expensive. Can leave cloddy seedbed and slug risk. Brings up weeds from seed bank.
Shallow cultivation (disc/tine)	Can be quick and cheap. Leaves finer seedbed. Favours mayweeds and parsley piert. Maintains wide diversity of invertebrate species.	Leaves straw on surface. Can result in more grass weeds, unless removed before drilling. Increased herbicide resistance risk.
Direct drilling	Quick. Cheap. Can result in fewer broad-leaved weeds.	Straw may need removing. Poor trash distribution may reduce efficacy of soil-applied herbicides. Needs suitable drill. Can result in more grass weeds, unless removed before drilling. Slugs. Can cause smearing in wet conditions. Best suited to well structured soils. Increased herbicide resistance risk.
Sowing date	*Large impact on weed numbers and species present*	
Early sowing	Good crop establishment. Crop competes with weeds.	Reliant on good in-crop weed control. More weeds especially grass weeds. Higher risk of herbicide resistance developing.

Contd.

Table 18.1 *Contd.*

Option	Strengths	Weaknesses
Late sowing	Allows non-selective weed control before drilling. Can spread costs.	Can reduce yields and profitability.
Spring sowing	Decreased grass weeds. Increased weeds that benefit wildlife.	Very dependent on spring soil conditions and weather. Less profitable on heavy soils.
Herbicides	*Large impact on weed numbers*	
Non-selective	Very effective control pre-drilling.	Could give delay in drilling to allow kill.
Selective	Very effective on wide range of weeds. Wide range of products available. Rate can be tailored to species present and size.	Herbicide resistance can develop if relying on a few modes of action. Can kill desirable as well as target weeds. Some products require ploughing or deep cultivation to disperse residues. May restrict subsequent cropping.
Crop competition	*Some impact on weed numbers*	
	Reduced environmental impact and cost.	Often not reliable enough to give adequate results.
Mechanical weeding	*Good impact on some weed species*	
Finger tine	Effective at reducing shallow rooted weeds.	Poor control of deep-rooted weeds. Needs dry soil conditions. Can damage nesting birds.
Inter-row hoe	Allows very vigorous weeding between crop rows	Needs accurate guidance. Can damage nesting birds.
Prevent weed seed spread	*Good impact on some weed species*	
Cutting and removal, hand rouging, seed collecting	Very effective where practical. Best suited for species which produce seed after the crop is harvested (e.g. wild oats). Can prevent long-term problems by containing a patch/infestation.	Difficult to be effective for early- or low-seeding species. (e.g. chickweed, speedwell). Might result in crop loss. Can often be time-consuming.

in turn provide essential summer feed for birds. Many previously common plant species are now rare as arable weeds. It is therefore increasingly important to leave weeds which do not affect the economics of the current crop. This is easiest to implement either where good control can be achieved before the next crop, where control in the following crop is straightforward and reliable, or where they will not cause problems in subsequent crops.

For each crop we can list which weeds can be tolerated in the crop because they have less impact, and those whose occurrence cannot be accepted. One way of ranking weed species is to consider the number of plants required to achieve a specific level of reduction in crop yield. An example of such a list for wheat is given in Table 18.2. Wheat is normally the least competitive winter cereal. Oats and barley compete with weeds more effectively.

Table 18.2 Tolerance ranking of weeds in wheat in the UK (weed species with a lower tolerance index produce the greatest yield reductions)*

Common name	Scientific name	Tolerance index	Biodiversity value
Annual meadow-grass	*Poa annua*	3	Feed for birds
Barren brome	*Anisantha sterilis*	0	
Black bindweed	*Fallopia convolvulus*	4	Feed for birds
Blackgrass	*Alopecurus myosuroides*	0	
Campion	*Silene vulgaris*	2	
Charlock/mustard	*Sinapis* spp.	1	Feed for birds
Chickweed	*Stellaria media*	2	Feed for birds
Cleavers	*Galium aparine*	0	
Couch	*Elytrigia repens*	0	
Crane's-bill	*Geranium* spp.	3	
Fat hen	*Chenopodium album*	2	Feed for birds
Field forget-me-not	*Myosotis arvensis*	2	
Field pansy	*Viola arvensis*	4	
Fool's parsley	*Aethusa cynapium*	3	
Fumitory	*Fumaria officinalis*	3	Feed for birds
Groundsel	*Senecio vulgare*	3	
Italian rye grass	*Lolium multiflorum*	0	
Knotgrass	*Polygonum aviculare*	3	Feed for birds
Mayweed	*Matricaria perforata*	1	Feed for birds
Meadow brome	*Bromus commutatus*	0	
Oilseed rape	*Brassica napus*	1	
Parsley piert	*Aphanes arvensis*	4	
Poppy	*Papaver* spp.	1	
Red dead-nettle	*Lamium purpureum*	3	Feed for birds
Redshank	*Polygonum maculosa*	2	Feed for birds
Scarlet pimpernel	*Anagallis arvensis*	3	
Sow thistle	*Sonchus* spp.	4	Feed for birds
Speedwell	*Veronica* spp.	3	Feed for birds
Thistle	*Cirsium* spp.	1	Feed for birds
Venus's-looking-glass	*Legousia hybrida*	4	
Wild oat	*Avena* spp.	0	
Wild onion	*Allium vineale*	4	

* Based on Blair *et al.* (1999). The tolerance index is related to numbers of plants which can be tolerated by the crop to give less than a 5% yield loss in winter wheat. This is as follows: 0 = not tolerated; 1 = up to 20 plants m^{-2} tolerated; 2 = 20–49 plants m^{-2} tolerated; 3 = 50–99 plants m^{-2} tolerated; 4 = more than 100 plants m^{-2} tolerated.

When should weeds be controlled?

Most weeds do not compete with the winter cereal crop until the spring (around growth stage (GS) 31), unless they are present at very high populations. However, there are advantages to removing weeds earlier. The benefits of autumn treatment include:

- Weeds are often easier to manage when they are small, and lower herbicide rates might be possible
- Weather and moist soils often result in better activity from residual herbicides
- Crop growth stage may restrict the choice of herbicide product in the spring
- There is a reduced need for complicated tank-mixes in the spring
- Time becomes available for attending to other crops in the spring

However, there are many cases where spring treatment will still be required. This is normally the case for wild oats and cleavers, but other weeds can emerge if crops are thin.

Can mapping weeds help?

Weeds typically occur in patches. This provides the opportunity to control the patch and prevent further spread, but also provides the opportunity to reduce costs by treating only the patches and not the whole field. Application equipment is available to treat a field in patches, but at present the ability to map a field cost-effectively is a major constraint to adopting this technology.

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Chapter 19
Weed Control in other Arable and Field Vegetable Crops

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Introduction

This chapter deals with UK crops other than cereals, including oilseed and protein crops, sugar beet, annual vegetables and forage crops. The crop, its method of culture, its place in the rotation, and the market for the end product, together with herbicide availability, timing, trends in usage and crop tolerance, all affect weed control strategy. Non-chemical weed control is dealt with in Chapter 13 but organic methods are mentioned here, for some crops.

The growing systems

The speed with which the crop covers the ground is a major factor in suppressing weeds and can be increased by providing the best possible conditions for crop growth. Seed priming can ensure faster and more uniform emergence. However, some crops, such as onions, with slow initial growth and erect habit are naturally poor competitors.

Studies show that weed seed numbers range from 240 to 24 330/m^2 in the surface layers of soil cropped with vegetables. Whenever the soil is disturbed, a small proportion of the dormant seeds are stimulated to germinate; the finer the seedbed, the greater the numbers which germinate.

Mechanisation of crop production has increased, and most crops are now grown on a field scale with almost total dependence on herbicides. This situation is likely to change in future with the loss of chemicals. Farms which specialise in high-value salad and vegetable crops carry a labour force for harvesting and preparation of produce for market which may be available for handwork and inter-row cultivations, so reduced herbicide use is still possible. However, it is becoming more difficult to attract UK labour for this type of work. The standard of weed control sought becomes higher as production methods increase in sophistication. For example, the weed interference tolerated in hand-harvested over-wintered spring cabbage is unacceptable in a short-season, mechanically harvested crop of calabrese grown for quick freezing.

In most crops, as weed control with herbicides has removed the need for inter-row cultivations, row widths can be reduced, with consequent changes in plant populations. However, some husbandry changes have taken place regardless of potential weed control problems. The development of methods for mass-producing modular transplants and new transplanting techniques has changed weed control in crops such as calabrese and celery. These transplants can be more sensitive to herbicide damage, but existing recommendations have been developed for bare-root transplants. There is now widespread use of floating plastic film in the UK. One objective is earliness, but there are also improvements in emergence, yield and quality, yet few herbicide labels refer to these techniques. Problems include residual herbicides having no effect because the soil surface dries out, restricted leaching causing herbicide residues to remain near the soil surface, and because of warmer conditions some weeds germinating early and growing too big for control by herbicides when the cover is removed. Soil sterilants provide an alternative means of weed control for crops grown under cover.

For organic production, aspects of the growing system such as plant density, row width and harvesting method will influence strategies for weeding; alternatively systems may need to be adapted to suit weed control techniques.

Market requirements

The market outlet, whether for processing, fresh market, compounding for animal feed, crushing, seed or organic produce plays an important role in determining the methods used for weed control.

The Food and Environment Protection Act 1985 (FEPA) provides Ministers with powers to regulate the import, sale, supply, storage, use and advertisement of pesticides, both generally and in relation to specific products. The controls set out in the Act are detailed and implemented through the Control of Pesticides Regulations 1986 (COPR). The Regulations prohibit the advertisement, sale, supply, storage or use of pesticides unless they are approved and unless certain general obligations and specific conditions are met. The Plant Protection Products Regulations 1995 (PPPR) were introduced to implement European Council Directive 91/414/EEC, concerning the placing of plant protection products on the market. These regulations provide for the implementation of a Community-wide system for controlling the sale and supply of plant protection products in the UK. Users of pesticides are also obliged to comply with pesticide maximum residue limits (MRLs) where these have been set via Community and UK legislation for specified pesticide/food crop, or feedstuff, combinations (see also Chapter 7). Samples of produce are tested for residues by processors, growers and retailers, and checks are made by the DEFRA Pesticide Safety Directorate. In addition, there is a requirement that herbicides used in a crop must leave no taint or 'off-flavour'. Processors require that pesticides are tested and cleared before use is permitted. The processor has a duty to the consumer to provide food in which MRLs are not exceeded and which is of wholesome quality and free from taint.

Markets for horticultural crops demand uniformity in size, quality, maturity and continuity of supply. Any treatment which causes blemishes or malformation of produce, uneven or delayed maturity, or a wide size range distribution is unacceptable and these aspects have to be considered during herbicide development.

Seeds may not be marketed unless they have been officially certified. To obtain certification the seed crop must pass official field inspection and the harvested seed must, after cleaning, meet the minimum prescribed standards. Some weed species are scheduled in the Seeds Regulations and the details of those statutory requirements are available from the Seed Production Branch, National Institute of Agricultural Botany, Huntingdon Road, Cambridge. In all crop certification schemes there is a general requirement that crops shall not be so weedy that a proper inspection for trueness to variety cannot be carried out. In addition, any herbicide treatment used must not cause damage effects which mask symptoms of disease and thus prevent thorough crop inspection. Seed for organic crops must itself be grown organically, although until organic seed production is developed for each crop variety it is possible to obtain permission to use non-organic seeds.

There is an increasing interest in organically grown produce in the UK. Organic production of fresh vegetables is rising, but the market is under-supplied. The processed crops are imported mainly from the USA and the Netherlands; UK production is at an experimental stage. Weedy contaminants, particularly poisonous ones, are a risk in some machine-harvested crops. Guidelines for achieving weed control while attaining organic quality standard are laid down by the Soil Association. The UK Register of Organic Food Standards (UKROFS) is the national authority responsible for implementing the EC legislation regarding organic production in the UK, and for certification.

Weeds and crop rotations

Annual weeds are usually the major problem in annual crops and both previous cropping and soil type influence the number and species of weeds occurring. Broad-leaved crops are at present grown in rotation with cereals and the intensive winter cereal production in the UK, with earlier sowing and minimum cultivation techniques, results in problems with weeds such as blackgrass (*Alopecurus myosuroides*) and volunteer cereals, and also perennial weeds such as creeping thistle (*Cirsium arvense*). These problems in broad-leaved crops are expected to increase following changes in the EU Common Agricultural Policy from 2000 and the expansion of the cereal area in the UK.

The consequences of set-aside schemes where arable land is taken out of production are difficult to predict. Seed banks will increase and some weed problems, particularly with perennial species, may increase.

There is also concern that if genetically modified (GM) herbicide-tolerant crops are introduced and if there is gene flow to related wild species, both these species and volunteers will be difficult to control. Volunteers from a crop tolerant to more than one herbicide will further complicate weed control. The effect on the environment is being considered before the release of GM crops. However, herbicide-tolerant GM crops can simplify production and greatly reduce the number of herbicide applications, for example in sugar beet.

Particular difficulties in control arise when the prevalent weeds are botanically related to the crop, e.g. where Cruciferae occur in brassica crops or Compositae in lettuce. There are often few, or no, herbicides selective in such circumstances.

Reasons for controlling weeds

Competition

Weeds that emerge before or with the crop usually cause the greatest yield reduction by competing for light, moisture and nutrients; tall species which shade the crop are particularly damaging. There have been several studies on the 'critical period' or the optimum time for weed removal in vegetable crops. The relationship between the density of certain weed species and yield loss has been investigated for some broad-leaved crops and levels of weed density tolerated by the crop (thresholds) before there are yield penalties have been suggested. In vegetables, however, marketable quality is the overriding factor.

Crop quality

The value of some crops is determined by the quality of the produce. Size and uniformity are the main criteria in vegetables such as onions, and these can be reduced by weeds. Weedy contaminants which are difficult and costly to remove at the factory or packing-shed downgrade the crop, and poisonous contaminants such as berries of black nightshade (*Solanum nigrum*) in vining peas may cause crop rejection. In crops grown for seed, complete removal of weed seeds which ripen with the crop and are of similar shape, weight and size is not practicable. Some species are also scheduled under the Seed Regulations; if limits are exceeded, the crop may be rejected for certification for seed. For example, in rape seed the content of charlock (*Sinapis arvensis*) shall not exceed 0.3% and there are standards for dock (*Rumex* spp.) in kale and swede, for blackgrass (*Alopecurus myosuroides*) in linseed and for wild-oat (*Avena fatua*) and dodders (*Cuscuta* spp.) in most crops, although dodders occurs infrequently.

Harvesting

Crops which are mechanically harvested must be free from weeds that may interfere with the operation, e.g. woody or climbing species such as cleavers (*Galium aparine*) and black-bindweed (*Fallopia convolvulus*). These climbing weeds sometimes cause crops to lodge, thus adding to harvesting difficulties. Use of a desiccant as a harvesting aid to kill weed growth adds to production costs. Some species such as small nettle (*Urtica urens*) and creeping thistle (*Cirsium arvense*) in a hand-harvested crop are objectionable to pickers, or obstruct access and slow down picking – a major cost.

Pests and diseases

Weeds are hosts to a wide range of pests and diseases which also affect the crop. Shepherd's purse (*Capsella bursa-pastoris*) is a host to *Sclerotinia sclerotiorum*, a fungus which causes disease in oilseed rape and peas; perennial fleshy rooted species of weeds are hosts to a fungal disease of carrots caused by *Helicobasidium purpureum*; many Cruciferae are alternative hosts to club-root, a disease caused by the endoparasitic slime mould *Plasmodiophora brassicae* and affecting most commercially grown brassicas; and chickweed (*Stellaria media*) seed can carry lettuce mosaic virus. Common couch (*Elytrigia repens*) and volunteer cereals are hosts to cereal diseases and if these weeds are not controlled in the 'break' crop they act as a 'green bridge', carrying over disease.

However, some weeds attract useful predators, e.g. mayweeds (species of *Matricaria*) attract hoverfly, an aphid predator.

Maturity

Most horticultural crops are sown and planted over long growing seasons to provide a continuous supply to processors and supermarkets of uniformly mature produce. Weed problems which cause delayed or uneven maturity must therefore be avoided. Weeds will also delay senescence and drying out of a crop harvested at the dry seed stage.

Effect on other crops in the rotation

Weeds are more likely to set mature seed in crops with longer growing periods and less likely to do so in short-term vegetable crops. A weed species which is of no consequence in one crop can well prove a problem in another; weed-beet, for example, is not a nuisance in cereals but it is a serious one in sugar beet. Herbicides which are used more frequently at a reduced dose rate in an attempt to cut costs may prevent competition from cleavers in cereals, but the small stunted cleavers which remain and set viable seeds may be costly to control in a following crop, e.g. field beans.

Integrated crop management and weed control with herbicides

Integrated crop management (ICM) forms a large part of weed control (Chapter 14). However, weed thresholds have yet to be developed for several crops, and where weed contaminants affect quality there is zero tolerance. Many retailers and processors source UK vegetables grown to 'Assured Produce' protocols, which include guidelines on ICM and environmental issues as well as lists of Approved active ingredients and Specific Off-Label Approved products for each crop. Through farm audits and traceability, the consumer is assured of safety of produce; this system is the most advanced in Europe.

Residual herbicides, applied at a dose often dependent on soil type, are used in most crops. Disadvantages are that activity is usually reduced under dry soil conditions, and that several are not safe for use on very light soils, or are ineffective on highly organic soils. The residues of some materials persist in the soil, restricting the choice of the following crop; this is a particular problem if the treated crop fails. The choice of a residual herbicide to suit the anticipated weed flora is not always easy.

Foliar-applied herbicides have often a restricted weed range, and development of more broad-spectrum, selective herbicides would do much to improve weed control in some horticultural crops. Therefore sequential treatments are often used, which may control complementary weed spectra or extend the period of control. There is also increased use of mixtures of active ingredients, either in a formulation or as a tank-mix, to broaden the weed spectrum.

Selective application to weeds of a non-selective herbicide, usually glyphosate, by means of a rope-wick or other applicator which utilises the height differential between crop and weed, has proved useful in a few situations.

Weed control with reduced or no herbicides

This aspect will become more important with the loss of several herbicides. Mechanical weed control and other methods will then be used.

Methods of weed control with no herbicide inputs are discussed in Chapter 13. There is a need for further development and evaluation of new mechanical weeders, black plastic covers, exclusion of light during cultivation, flame weeding, field steam and dry heat sterilisation and other methods for weed control in vegetable crops.

Available herbicides

The extent of herbicide development in crops other than cereals is a reflection of crop area, and there is therefore a wide range of herbicides for oilseed rape and sugar beet. However, growers of many minor crops have few herbicides at their disposal since development costs are high, sales are small and a damage claim in a high-value crop could be considerable. Reliance has been placed on materials approved for other crops. Resources for independent evaluation of herbicides in minor crops have also been reduced. Non-approved use of pesticides is an offence under the Control of Pesticide Regulations 1986.

In addition to pesticide use approved on a label for major crops there is a UK system where a Specific Off-Label Approval (SOLA) may be granted by the UK Pesticide Safety Directorate, usually for a minor crop use, and residues data are often required. Such pesticides are applied at grower's risk and there is no guarantee of safety to the crops. These SOLAs are sought by growers and funded by growers' levy, in the case of horticultural crops, by the Horticultural Development Council.

An on-label use or a SOLA for a pesticide for one crop can sometimes be extrapolated to another, minor one provided the crop morphology, harvest time and other factors are similar; for example, swedes can be extrapolated to turnips. However, usage, as with SOLAs, is at grower's risk. Both of these systems are of tremendous benefit to growers, and without them some crops could not be grown or it would be uneconomic to do so. The current extrapolations are shown in Table 19.1.

However, some pesticide uses have been lost because lack of supporting data from agrochemical companies has led to MRLs set by the EU at the limit of detection. In future an MRL will be set for all pesticides listed on Annex 1 and this will include herbicides.

In addition a review of pesticides registered in 1993, or before, has been undertaken by the European Commission (EC) to ensure that older pesticides meet modern standards of safety. It became clear in 2000 that a large number of active ingredients in herbicides would not be supported in the reviews by agrochemical companies. The reasons are mainly commercial because the high cost of generating modern data packages for many of the older chemicals only used in minor markets could not be justified. Many on-label registrations will cease from 25 July 2003, and several herbicides may become unavailable before that date. As a result SOLAs and extrapolations for minor crops will also be lost. Even where active ingredients are supported, not all crop uses will be retained. There is a possibility that a few of these herbicides may be retained as 'Essential Uses' in the EU for a short period possibly four years after 2003 to allow time for alternatives to be developed. Decisions by the European Parliament and by the European Commission concerning which pesticides will remain were made in June 2002 but not known at the time of writing this chapter. In future, mutual recognition across EU Member States of pesticides which are eventually included in Annexe 1 may ease the difficulties in minor crops.

A crisis threatens EU production of not only important high-value crops grown on a small area, but some major ones as well.

Reliance on a narrowing range of active ingredients in a widening range of crops will increase the problem of developing tolerant weed flora and it will also increase the risk of herbicide resistance occurring.

The following sections provide information on the main challenges for weed management in a range of crops and describe some current and future options.

Table 19.1 Vegetable crops included in the UK long-term arrangements 2002 for extension of use (valid until 31 December 2004)

Column 1: Crops on which use is approved	Column 2: Minor use
carrot or radish	parsley root
sugar beet	fodder beet, mangel
carrot or radish	horseradish
carrot	parsnip
carrot or celeriac	salsify
turnip	swede
swede	turnip
bulb onion	garlic, shallot
tomato	aubergine
melon	squash, pumpkin, marrow, watermelon
calabrese	broccoli
broccoli	calabrese
cauliflower	Roscoff cauliflower
kale	collards
lettuce	lamb's lettuce, frisée/frise, radicchio, cress, spinach
lettuce or spinach or parsley or sage or mint or tarragon	leaf herbs and edible flowers
spinach	beet leaves, red chard, white chard, yellow chard
edible podded beans	edible podded peas (e.g. mange-tout, sugar snap)
dwarf French beans	runner beans
celery	rhubarb, cardoon
mushroom	edible fungi other than mushroom (e.g. oyster mushroom)
lettuce	leafy brassic crops grown for baby leaf production
salad onion	leek
sweet pepper	cayenne pepper
vining pea	broad beans

Clarification: The following field crops are considered to be synonymous; uses on crops in Column 1 can be read across to uses in Column 2

Column 1: Crops on which use is approved	Column 2: Minor use
French bean	navy bean
vining pea	picking pea, shelling pea, non-edible podded pea
linseed	linola, flax

* Source: Pesticide Safety Directorate.

† There are also extrapolations from oilseed rape to linseed (and other minor crops) and from combining peas or field beans to lupins.

All these uses are at the user's choosing and the commercial risk is entirely theirs.

It is the responsibility of the user to ensure that the proposed use does not result in any statutory UK MRL being exceeded. These extrapolations may **not** be used where the MRL for the crop in column 2 is set at the limit of determination, or is lower than the MRL for the crop in column 1, or where an MRL has been established for the crop in column 2 but not for the crop in column 1.

Brassicas for forage, stockfeed and oilseed

Kale

Kale is often direct-drilled in June into grass swards which have been destroyed with glyphosate, and weed control presents little difficulty. Row widths vary from 110 to 450 mm. Although kale is sensitive to weed competition during the first few weeks, once the leaves have met across the rows the crop effectively suppresses weeds.

The main problem weeds in kale are fat hen (*Chenopodium album*), *Polygonum* spp., mayweeds and chickweed, and where kale is grown intensively there may be a build-up of charlock. Shepherd's purse is rapidly overgrown by the crop but still produces substantial numbers of seeds. Common couch persists throughout the life of the crop and the underground rhizomes survive the treading of livestock.

There are recommendations for application of trifluralin pre-sowing and of some other brassica herbicides pre-emergence, but these are generally considered too costly. Clopyralid alone or in a tank-mix is used to control creeping thistle and other Compositae. Propyzamide can only be used on kale seed crops.

Forage rape and quick-growing (stubble) turnips

These catch crops are of short duration and low value and little is spent on weed control. Forage rape and stubble turnips are broadcast, or drilled on narrow rows, from June to August for use from September to December, and they establish quickly.

They often follow cereals, so volunteer cereals are the most frequent problem; control is with fluazifop-p-butyl which has a SOLA for stockfeed only. The possible effects of residues of herbicides, e.g. clopyralid, on following crops must be considered since rape and stubble turnips are short-season crops.

Swedes, turnips and kohl rabi

Swedes and turnips are grown for culinary use as well as stockfeed, and are more suited to moister, cooler areas. They are usually precision-drilled on wide rows and in the north of the UK are sometimes grown on ridges. Some crops are grown under plastic film to achieve earliness for the ware market.

Weed problems are similar to those of kale but swedes and turnips are less effective at covering the ground and are thus more susceptible to weed competition, particularly for the first eight weeks after emergence. Weeds also interfere with mechanical harvesting.

In fodder crops most growers use only one herbicide followed by mechanical cultivation. There is greater emphasis on effective weed control in the higher-value culinary swedes and turnips and sequential programmes are run with trifluralin incorporated pre-sowing, followed by a residual treatment. Most brassica herbicides are approved for use in swedes and extrapolated to turnips from swedes under the arrangement for minor uses. Foliar-acting treatment for broad-leaved weeds is limited to clopyralid. Cycloxydim, propaquizafop and fluazifop-p-butyl (stockfeed only) can be used for volunteer cereals and some grass weeds.

Blemishes or malformations of swede and turnip roots caused by herbicides or mechanical methods are unacceptable in crops for human consumption.

For organic production weed control is with inter-row cultivations with tractor-drawn hoes, and hand-hoeing within the row.

Kohl rabi is grown on warm soils because quick growth is essential. It is planted on beds and some crops are covered by plastic film or fleece to achieve earliness. The crop develops quickly and competitiveness with weeds is better than for swedes. However, the arrangement for extrapolation to minor use in kohl rabi no longer exists, so this now suffers from a lack of approved pesticides. Brassica herbicides trifluralin, propachlor and prometryn have SOLAs, but prometryn was not supported in the EC review.

Oilseed rape

Oilseed rape as an edible oilseed receives EU arable aid, and after reductions in premiums from the year 2000 the area grown has declined. It is also grown for industrial uses, for which there is no support. Growers have examined the variable costs of oilseed rape and weed control appears to be a candidate for reduction.

Most oilseed rape is sown at the end of August or in early September (winter oilseed rape) on close rows 115–200 mm apart. Growth is rapid and the crops compete strongly with weeds both in autumn and spring, but those with low vigour or poor establishment are vulnerable to weed competition.

Oilseed rape is often drilled into cereal stubbles with insufficient time to control volunteer cereals before sowing. Volunteer cereals (particularly barley, which grows vigorously in autumn) are the most serious problem in winter oilseed rape but experiments have shown that vigorous crops can tolerate high populations without yield loss. Economic weed control thresholds for volunteer barley have been suggested by Lutman (1989) to vary from 100 plants/m^2 for early-sown crops, down to only 15 plants/m^2 for crops which are late-sown or with poor vigour. Blackgrass is also competitive if large numbers emerge at the same time as the crop. Cleavers is the most yield-damaging broad-leaved weed and it also causes harvesting difficulties. Surveys suggest that occurrence of cleavers is increasing, probably as a result of incomplete control in cereals if low herbicide doses are used. Common chickweed is troublesome because of its vigorous growth during winter. Mayweeds can affect backward crops.

Return of weed seeds poses a threat to the following cereal crop. In winter rape cleavers and also common poppy (*Papaver rhoeas*), which cannot be easily controlled in oilseed rape, are particular problems; similarly, charlock presents difficulties in the spring-sown crop.

Some weed species affect seed quality for crushing: seeds of cleavers and the cruciferous species charlock and wild radish (*Raphanus raphanistrum*) are difficult or impossible to separate from the oilseed rape sample and there is a price deduction where admixture exceeds 2%. Produce may be rejected by the crusher if weed seeds adversely affect oil content or cause taint or discolouration of the oil.

In rape grown for seed production, some cruciferous weed species such as charlock and wild radish are scheduled in the Seed Regulations. These can only be rogued with extreme difficulty and fields known to have a high population should be avoided.

Winter oilseed rape

This used to be regarded as a cleaning crop in the cereal rotation but not all crops receive herbicides. Survey data for herbicide use suggest that there is an increasing reliance on post-emergence graminicides, but less is done to control broad-leaved weeds although there is a useful range of herbicides to control most weed species now; cleavers can be treated with quinmerac or clomazone formulated with metazachlor.

Activity of residual pre-emergence herbicides is reduced by dry or cloddy seedbeds (but so are weed numbers) and where some materials are absorbed onto straw residues. The selectivity of metazachlor pre-emergence depends on the drilling depth of the crop and it can be leached by heavy rainfall; this is a problem on light soils. A split pre- and post-emergence treatment can be used but several species, including cleavers, common poppy, shepherd's purse and field pansy (*Viola arvensis*), are more effectively controlled at the pre-emergence stage.

Post-emergence applications have to be timed according to the growth stage of the weed and crop and there is a key for stages of development of oilseed rape. In a dry autumn, oilseed rape emerges over a long period, which leads to problems of timing treatments in relation to crop safety. If application is delayed, soil conditions may have become too wet to allow the sprayer to travel, and the efficacy of some herbicides is reduced under cool conditions. Most foliar-acting herbicides are applied in autumn, but some are applied in spring in warm conditions where there is still an open crop canopy to allow spray penetration.

Clopyralid alone or with benazolin is used on actively growing weeds, mainly for mayweeds. Cyanazine, which was not supported in the EC review, applied post-emergence controls cruciferous weeds including charlock, but selectivity is dependent on adequate rape leaf wax. Pyridate (SOLA) for cleavers control is seldom used now. Tank-mixes improve control of difficult species; sequential applications are often necessary for cleavers.

Volunteer cereals, blackgrass, other annual grasses and some broad-leaved weeds can be killed with propyzamide applied post-emergence before the end of January, or the less persistent carbetamide; both have residual activity. Propyzamide/clopyralid is used where mayweeds are also a problem, but their use is declining. Blackgrass germinates over a long period, especially in a dry autumn, and some may become too large to be adequately controlled by the residual herbicide so a post-emergence graminicide is needed subsequently. Conversely, foliar-acting graminicides used for volunteer cereals are followed by residual herbicides applied to control late-emerging blackgrass. Many growers now rely on graminicides to which strains of blackgrass are becoming resistant, but this is an ill-advised policy from the point of view of the rotation as a whole. Where target site resistant blackgrass and wild-oats have been identified, triallate, metazachlor and propyzamide are useful.

A rape crop presents a useful opportunity to eradicate common couch with a pre-harvest application of glyphosate.

Spring-sown oilseed rape

This crop establishes and grows rapidly, smothering weeds. There are few herbicide recommendations for broad-leaved species. Propyzamide has no label recommendation, and those herbicides available have a limited weed spectrum. Many growers use a cheap herbicide such as trifluralin, or none at all. Wild-oats pose a greater threat and are treated where they occur.

Most of the rape crop is swathed before combine harvesting; about 33% is desiccated with diquat before harvesting but this is not usually done to kill green weeds.

Some oilseed rape herbicides are highly persistent in the soil. Mould-board ploughing is recommended before subsequent cropping where, for example, propyzamide is used. If oilseed rape fails to establish, often as a result of dry soil conditions, there are limitations on drilling an alternative crop and an interval must be left before sowing susceptible crops, or spring rape is sown instead. If failure is a possibility it would be better to use a foliar contact-acting herbicide. Oilseed rape is susceptible to some herbicides used in other crops and spray drift from growth regulators used in cereals to a rape crop in flower can cause damage. Ploughing before sowing the winter crop avoids volunteer cereals, but otherwise mechanical weeding is not used in oilseed rape.

In the future, weed control in oilseed rape could be simplified by the introduction of genetically modified varieties which are tolerant of herbicides such as glufosinate or glyphosate. Breeding programmes for winter and spring varieties are well advanced. However, at present GM crops are not acceptable to some sectors of the public or to some growers.

Volunteer oilseed rape

Oilseed rape volunteers have become an increasing and persistent problem in other broad-leaved crops. Harvesting techniques which avoid seed return and allow lost seed to germinate with subsequent cultivation (as opposed to seed burial which would aid survival) will prevent the volunteer problem to some extent (Pekrun *et al.*, 1996).

Isolation of industrial rape crops with high levels of erucic acid from edible crops will minimise cross-pollination and avoid volunteers from seed carryover which could cause contamination. In the future this could become even more relevant if 'designer rapes' are grown for specific oil contents, e.g. for high-value pharmaceutical use. If GM crops are introduced, control of modified rape volunteers elsewhere in the rotation will require careful planning.

Horticultural brassicas

Cabbage, cauliflower, Brussels sprouts, calabrese and sprouting broccoli are grown throughout the country on a range of soil types, the most suitable being moisture-retentive, alkaline, mineral soils. Cauliflower and cabbages are produced all the year round, and clear perforated plastic film is used for early production of these crops and for calabrese.

Where produce of small size is required (e.g. Brussels sprouts for processing, baby cauliflower and calabrese for small spear production), the seed is precision-drilled in the field at high density on narrow rows, and the crop canopy closes early. For drilled crops the cost of hybrid seed is high but the labour required is less.

Most brassica crops are grown on wide rows from transplants raised in a glasshouse in modular trays or blocks. Establishment is quicker and this technique has been a major aid to crop scheduling. Bare root transplants are used less frequently.

Good weed control is essential to maximise yield and to achieve crop uniformity and quality. Weeds compete with brassicas for nutrients and water and can delay maturity. The key period for weed control is the first four weeks after transplanting.

Horticultural brassicas are grown in arable rotations and inherit the weeds of previous arable crops and the crop volunteers (potatoes, oilseed rape and cereals). Where brassicas are intensively grown there may be a build-up of weeds tolerant to herbicides, e.g. in the case of shepherd's purse which can be a serious spring weed. Weeds which emerge in large numbers in autumn, e.g. annual meadow-grass (*Poa annua*), common chickweed and mayweeds, are the main problems in brassicas which are transplanted or drilled from July to September. Tall species such as fat-hen interfere with mechanical harvesting of Brussels sprouts; small nettle is unpleasant for hand pickers in calabrese and cauliflower. Weed seeds sometimes contaminate produce when the crop is wet. Fields known to have populations of weeds which are resistant to brassica herbicides, for example pennycress (*Thlapsi arvense*), should not be grown under plastic cover where mechanical weeding is not possible. Perennial species such as common couch, docks and thistles should be controlled before planting.

Where brassicas are transplanted, weeds are removed by cultivations or herbicides prior to transplanting, and rapid establishment allows the early use of post-planting treatments.

In most brassica crops weed control is achieved with a pre- or post-planting application of a residual herbicide and a fine moist soil is needed for good activity. This treatment may be followed by applications of foliar-acting herbicides, which may also have some residual activity, to emerged problem weeds; sometimes cultivations are used as well. It is important to avoid damage to brassicas. Fortunately several brassica herbicides are safe on all the main crop species, but some post-emergence materials are less safe on calabrese and cauliflower, which have less well-developed leaf wax. For example pyridate, which is contact-acting, is not for use in these crops.

Trifluralin, incorporated in the soil before sowing/planting, is cheap but controls a limited weed spectrum. Chlorthal-dimethyl must be applied before emergence of weeds, it can be used on drilled crops or any time after transplanting, and it has a wider weed spectrum than propachlor. However, this product is often in short supply. Propachlor is applied soon after drilling, after crops have three to four true leaves or on hardened-off transplants, but it fails to control *Polygonum* species or fat-hen so it is used in tank-mix with chlorthal-dimethyl where available. Tebutam, which was not supported in the EC review and has therefore been lost, was used before emergence of drilled crops or on hardened-off transplants but before weed emergence. Metazachlor is used before emergence, after the three true leaf stage of the drilled crop or to well established transplanted crops. Pendimethalin can only be applied before transplanting and care must be taken not to introduce treated soil to the root zone. It must not be used for drilled crops.

Modular or block transplants are particularly sensitive to herbicide damage and some labels include warnings that special care is needed (propachlor). At present no brassica herbicide label refers to protected crops except in the cases of propachlor and metazachlor, which are excluded from use on brassicas under glass or plastic cover.

It is sometimes necessary to use foliar contact-acting or translocated herbicides. Clopyralid is useful for control of mayweed, creeping thistle and volunteer potato suppression and is used alone or in tank-mix. Pyridate, approved only for use on cabbage and sprouts, provides useful control of cleavers. Cyanazine has a SOLA for calabrese, cabbage and cauliflower (and kale) as well; one for sprouts is being assessed. The long-term future of cyanazine is in doubt and sodium monochloroacetate, which was widely used for control of *Polygonum* spp., small nettle and field penny cress, was not supported in the EC review.

Maintenance of adequate harvest intervals after application of foliar-acting herbicides may be difficult in short-season crops.

Grass weeds in cabbage, cauliflower and Brussels sprouts are controlled with post-emergence graminicides cycloxydim or tepraloxydim (except sprouts), but no graminicide is approved for calabrese. In brassica seed crops propyzamide and carbetamide can be used, and the latter also has a label recommendation for spring cabbage.

Some herbicides which are persistent in the soil may be unsuitable in short-term brassicas and cropping options are limited in the event of crop failure. There are restrictions on the crops following trifluralin, tebutam and chlorthal-dimethyl, for example, and deep ploughing before redrilling or planting is required. Residues of clopyralid in soil or plant tissue may affect some succeeding crops and should not be applied later than July where susceptible crops (e.g. peas) are to be planted in spring; susceptible crops such as field beans must not be sown in the same year as treatment.

New herbicides are likely to be developed for brassicas as long as oilseed rape is an important crop, but they will not necessarily be safe for use in all horticultural brassicas.

Herbicide use can be reduced by using a 'stale seedbed' technique: the soil is cultivated and prepared several weeks in advance of cropping and the flush of weeds is killed with a non-selective herbicide (glyphosate, glufosinate-ammonium, paraquat or paraquat/diquat mixture) just before planting. This ensures a weed-free start. Mechanical weeders can be used later for crops on wide rows to control weeds between the rows: steerage hoes, brush or finger weeders and several new mechanical weeding machines have been developed. The aim is to give minimal soil disturbance in dry conditions and the soil is lightly thrown around the base of the stem to smother seedling weeds. It is difficult to control weeds within the crop row; an integrated system has been studied in which a herbicide is used over the rows, with mechanical weeding between them.

For growers who do not wish to use herbicides at all, weeding is done mechanically. Alternatively the crop can be planted through mulches of black polythene or other materials and some crops are covered with fleece to protect against insects. Organic cauliflowers are grown using mechanical hoeing and ridging up.

Sugar beet and related crops

This group of crops includes fodder beet and mangolds and the vegetable crop red beet (beetroot). Sugar beet occupies the greatest area and most of the UK crop is grown in eastern England. Technical development is most advanced in sugar beet; many techniques are transferred subsequently to the other crops in this group. Fodder beet and mangolds are used for animal feed and are grown throughout the UK, albeit on a relatively small scale.

Sugar beet, fodder beet and mangolds

Worldwide, approximately 60 species of important weeds are found in sugar beet fields. Usually ten or fewer main species are found in fields on any one farm, of which 70% or more are likely to be annual broad-leaved species. In the UK, creeping thistle, volunteer potatoes and common couch are three of the most important perennial weeds. Some of the most common annual broad-leaved species are fat hen, black-bindweed, redshank (*Persicaria macularа*), knotgrass (*Polygonum aviculare*), fool's parsley (*Aethusa cynapium*), volunteer oilseed rape, mayweeds (pineapple and scentless), cleavers, common chickweed, charlock, small nettle and field speedwell (*Veronica persira*). Annual meadow-grass and wild-oats are the most common annual grass weeds but are less important than most of the broad-leaved weeds. Sugar beet is grown in rotation with other arable crops, including cereals. A few cases of herbicide-tolerant blackgrass have been identified in sugar beet fields, but other herbicide-resistant weeds are not found.

Fodder beet and mangolds tend to suffer more than sugar beet from late-germinating weeds such as fat-hen and are also likely to be affected by grasses such as bents (*Agrostis* spp.), meadow-grass and common couch which have been encouraged by the previous cropping sequences. Weed control in these fodder beet and mangold crops tends to be poorer than in sugar beet, mainly through lack of specialised equipment and expertise.

Sugar beet is usually sown in March, after the main risk of cold spells has passed. Cold periods after drilling can vernalise sugar beet and cause it to bolt (i.e. form a flowering stem) and produce seed during its first year of growth. These seeds produce plants with primarily an annual habit, which become weeds in subsequent beet fields. Fodder beet and mangolds are usually sown from late March to early May. All the crops are harvested in the autumn or early winter.

Weed beet has become a serious problem in sugar beet and, by 2001, could be found in over 70% of fields. In the late 1960s and early 1970s various forms of annual beet were introduced as impurities in sugar beet seed. Weed beet seed can remain viable in the soil for many years; its longevity and dormancy are influenced by depth and time of burial after harvest. Short rotations with only a three-year break between sugar beet crops aggravate the problem but lack of control by growers in the 1990s led to an increase in the problem. Weed beet is often patchy in its distribution in beet fields.

Early in the growing season sugar beet is susceptible to weed competition, but once it reaches the six- to eight-leaf stage it can tolerate freshly emerging weeds. The most competitive weeds are broad-leaved ones that emerge before or at the same time as the beet and grow taller than the crop. Competition for light is usually more important than that for water or nutrients. Sugar beet can tolerate low-growing, late-emerging weeds such as scarlet pimpernel (*Anagallis arvensis*) and field pansy. Some species such as knotgrass can cause difficulty at harvest by wrapping around moving parts and stopping harvesting machinery. Woody species such as fat-hen can blunt the knives employed on some older harvesters. The presence of weeds and trash in storage clamps can reduce air flow through the stored crop and cause increased respiration of the beet so that sugar or dry matter is lost. However, most modern, self-propelled, multi-row harvesters can cope with moderate weed populations and also prevent trash being harvested. Thus the greatest problem caused by uncontrolled weeds in modern-day beet crops is loss of yield.

Herbicides provide the main method of weed control in sugar beet. Until the 1980s most herbicides were applied over the rows only, as band sprays, and the weeds between the rows were controlled by tractor hoeing. This system is still used in some fodder beet and mangold crops but it is used in only a few sugar beet fields. At least three times more labour is required than where overall sprayers are employed. Herbicides are now applied in what is commonly known as the repeat low-dose, low-volume technique. In this system post-emergence herbicides are applied as fine-quality sprays in spray volumes of ca 100 l/ha. A sequence of treatments, each consisting of two or more herbicides in mixture, is used with usually three (mineral soils) to six (organic soils) sprays being applied. The mixes usually contain both contact-acting and residual active ingredients. Phenmedipham is used in the majority of post-emergence mixtures, often in combination with desmedipham and/or ethofumesate. Whilst ethofumesate provides some residual activity, metamitron, lenacil and chloridazon are the most common herbicides included as residual acting components. Triflusulfuron-methyl is used to improve control of *Brassica* species, especially volunteer rape, and other species such as cleavers, fool's parsley and small nettle. Clopyralid is important for the control of creeping thistle and is also used for the control of volunteer potatoes and to improve control of mayweeds. Most annual and perennial grass weeds are usually controlled post-emergence with specific graminicides fluazifop-p-butyl, cycloxidim, tepraloxydim and propaquizafop. Annual meadow-grass is an exception and is usually controlled by means of a residual herbicide in a post-emergence mixture. These graminicides are also employed to control barley cover-crops that are sown on some very light sand and peat soils to reduce wind erosion.

Most herbicides used for broad-leaved weed control in beet crops give the best control when weeds are small and at the cotyledon stage. The fine sprays are used to give good cover and contact on these small weeds. Adjuvant oils are often added to spray mixes to improve the contact effect of the herbicides. Timing of spray treatments is critical but can often be delayed by poor spraying conditions. Therefore, on many fields a pre-emergence herbicide (usually chloridazon but sometimes with the addition of quinmerac where cleavers or fools parsley are expected) is applied to provide some leeway in timing of the first post-emergence spray and, for this reason, pre-emergence treatments are particularly important in fodder crops. Where pre-emergence herbicides are used, one fewer post-emergence spray is normally required. Pre-drilling herbicides are confined to contact herbicides such as glyphosate or paraquat + diquat to control weeds that have emerged before seedbed cultivation. Wheelings prior to drilling are kept to a minimum because they have an adverse effect on crop establishment. Many growers are adopting a tramline system to reduce the effect of traffic on the beet growing next to wheelings in the crop.

The main factor influencing choice of herbicide – whether alone, as part of a mixture or in a sequential spray programme – is efficacy. A deficiency in the spectrum of weeds controlled by an early treatment may be acceptable, provided that a follow-up treatment or treatments can deal with it. Because sugar and fodder beet and mangolds are usually grown to a stand, crop safety is a prime consideration for all treatments that may be used, but especially those that are applied to freshly emerged cotyledon-stage beet.

As for all crops, only approved pesticides can be used on beet crops. In the UK, an auditing system is included in the contracts between sugar beet growers and the processor. Most herbicides are approved for use in sugar beet only and few are approved specifically for use on fodder beet and mangolds, owing to the relatively small area of these crops that is grown. However, herbicides approved for sugar beet can be used in these beet crops under The Revised Long Term Arrangements for Extension of Use (2002) regulations. Most herbicides are applied to beet before the canopy meets across the rows in June. Thus there is a long interval before harvest can take place. However, specific harvest intervals or latest time of application are specified in the Approval of each herbicide.

Most sugar beet varieties are diploid or triploid but there are no specific differences in herbicide tolerance between varieties of sugar beet, fodder beet or mangold varieties.

Tractor hoeing between the rows is still used as part of the weed control programme on many sugar beet fields, especially where weed beet are present. At one stage hoeing was necessary to remove unwanted beet from overlapping rows on headlands. These caused problems with the single-, double- or triple-row harvesters used at the time. Nowadays such hoeing is not necessary as the majority of sugar beet is harvested with six-row self-propelled machines that can cope with such overlaps.

Control of weed beet is achieved by a combination of methods, including tractor hoeing to control weed beet emerging between the beet rows. Hand pulling is used for light populations (< 1000/ha). Weed wipers are used to apply glyphosate to flowering stems growing above the crop (for populations < 10 000/ha) whilst cutting is used to reduce seed return from very high (> 10 000/ha) populations.

At harvest, beet tops and crowns are left in the field. Crowns, along with any beet missed by the harvester, can regrow in the subsequent crop in the rotation. These are easily controlled in cereals (which usually follow beet) by sulfonylurea or other herbicides, and are seldom a problem.

A major problem for sugar beet growers is the selection and correct application timing of the current herbicide treatments. Fodder beet and sugar beet have been developed by genetic manipulation to be tolerant to glyphosate or glufosinate-ammonium. Such varieties would obviate the need for herbicide mixtures and allow flexibility in timing of treatments. Other benefits associated with later and/or more flexible timing of treatment might also accrue from such developments.

Red beet

Red beet are grown for the fresh market or for processing, including pickling. The crop is best suited to soils where roots are able to grow without restriction. Crops are sown with pneumatic precision seeders to obtain roots of uniform size. Red beet for early harvesting in June/July are drilled in February or early March at low density to achieve the maximum amount of light and the beds are covered in clear plastic film or non-woven fleece to warm the soil. The covers are removed when the seedlings are well developed. Main-season and late crops are drilled from March to June. Red beet for bunching and baby beet are grown at close spacing on 300 mm row widths. Irrigation is essential, particularly for early crops.

Root size and marketability, as well as yield and harvestability, are affected by weed competition. Weed problems in red beet are similar to those in sugar beet. Weed beet can only be removed by machine-topping, hand-pulling or weed-wiping the flowering shoots, so fields where these occur should not be covered with plastic film where mechanical control is not possible.

Several sugar beet herbicides also have a label recommendation for red beet: lenacil at pre-emergence; phenmedipham, ethofumesate and clopyralid; and a SOLA for triflusulfuron-methyl, which is useful for cleavers control. The spray programmes may include sequential low-dose post-emergence applications in order to control late-germinating weeds with metamitron, which reduces the need for hoeing.

Weed control without herbicides is possible with mechanical weeders but this is seldom done except for organic production, where a stale seedbed followed by brush weeders or steerage hoes, together with hand weeding within rows, are the methods used. Red beet may also be grown on ridges, weeds being controlled by ridging cultivations.

Spinach

Spinach is grown for processing and fresh market and it is becoming increasingly popular as a constituent of leaf salads. It is harvested from the end of April until the beginning of November. Whole leaves of the crop are machine-harvested and therefore no weeds can be tolerated.

Only one residual herbicide, chlorpropham/fenuron, has a label recommendation for spinach, and fenuron was not supported in the EC review. Most spinach is treated pre-emergence with lenacil, a sugar beet herbicide, which has a SOLA. It is more persistent and a three-month interval is required between application and planting of the following crop. For the future a residual herbicide with short persistence and which is effective on a wide spectrum of broad-leaved weeds including black nightshade is needed. There is a SOLA for contact-acting phenmedipham post-emergence, but this can be damaging, and there is also one for clopyralid, which is used for mayweed and thistle control.

Where pesticide residues could be a problem in spinach for baby and infant foods, and for 'baby leaf' salads, the soil is sterilised before sowing. Sterilisation with methyl bromide is being replaced by field steam sterilisation.

Potatoes

The area of potatoes has declined to around 140 000 ha and the majority is now grown on light to medium texture soils with irrigation. Yields have continued to rise with improved husbandry. Potatoes are grown for human consumption (ware) as first earlies, second earlies or main crop, although the difference between these classes is becoming less distinct and a proportion of the crop is grown for seed, mainly in Scotland. The crop offers good weed suppression once established but yields are reduced by severe weed infestations. Yield loss is related to time of weed emergence; weeds which emerge early are the most competitive and damaging. Weeds also influence tuber size and affect rate and ease of harvesting, particularly species with a strong stem such as fat-hen and volunteer oilseed rape.

The normal spectrum of annual weeds occurs in potatoes, and cleavers appear to be increasing. Perennial grass and broad-leaved species such as creeping thistle, common couch and colts-foot (*Tussilago farfara*) can be a problem in main-crop potatoes.

The weed control requirements and limitations depend on the market outlet. For example, in potato seed crops herbicides that are applied post-emergence and that distort or discolour crop foliage, thus masking symptoms of virus disease, may result in rejection for seed certification and must therefore be avoided. It should also be noted that spray drift or sprayer contamination with certain herbicides, such as glyphosate or clopyralid, can affect the growth of progeny tubers. Where this is suspected the progeny need to be tested for any abnormal growth before they are used for seed.

Husbandry can influence the method of weed control. Potatoes are grown on ridges on wide rows, stone and clod separators are frequently used and weeds growing in rows of collected stones and clods are controlled with foliar-applied herbicides. Early potatoes produced under protection of clear floating plastic film or woven fleece are sprayed early pre-emergence before covering, but weeds which escape control cannot be removed with late pre-emergence herbicides or with cultivations.

Potatoes were traditionally regarded as a cleaning crop and in the past weeds were controlled with repeated cultivations which caused root damage and some yield loss. Now weed control is achieved mainly with herbicides. Recently environmental concerns and the need to examine costs have generated renewed interest in mechanical weed control and new methods may appear attractive to growers on weedy land, especially where highly organic soil limits herbicide options. These mechanical methods are often integrated with chemical control.

Herbicides with contact action need weeds present but no crop, whilst residual herbicides need a settled ridge and moisture to activate them and applications must be made when wind speeds are low to ensure an even cover on both sides of the ridge. In practice, growers on mineral soils use a tank-mix of a contact and a residual herbicide applied shortly before the beginning of crop emergence. This maximises the effect of both, by reducing the interval between herbicide application and competition by the crop.

The contact-acting herbicides paraquat or paraquat/diquat are used to kill weed seedlings which emerge before the crop. Damage to any potatoes which have already emerged is often only temporary.

Soil residual herbicides for potatoes also have some contact action and most produce temporary damage symptoms on crop leaves – hence their use pre-emergence. Linuron is commonly used and is more effective than other herbicides for pre-emergence control of weeds, but it gives poor control of fumitory. Chlomazone controls cleavers. Metribuzin has the most contact activity and is the most persistent of the currently recommended residual herbicides; it controls oilseed rape volunteers, but there are varietal restrictions especially after emergence of the crop. Increased activity of metribuzin on soils containing over 10% organic matter is achieved by incorporation into the ridge pre- or post-planting.

Post-emergence rimsulfuron, a sulfonylurea which has systemic foliar activity, is safe on all varieties and is used to control volunteer oilseed rape and a range of late-emerging broad-leaved and grass weeds. It can cause temporary mottling of foliage, masking symptoms of some virus diseases, and therefore cannot be used on seed crops. Other post-emergence options for broad-leaved weed control include contact-acting bentazone, applied with or without adjuvant oil, and metribuzin; both have varietal restrictions. However, they degrade rapidly and there are no rotational or ploughing requirements.

Post-emergence graminicides are applied to only a small percentage of the crop, and most growers rely on glyphosate applied pre-harvest or in stubble of a preceding cereal crop to reduce perennial grass weed problems.

Although some herbicide active ingredients were lost as a result of EC reviews, the range now available is sufficient to meet the needs of potato growers, but the future of some of them is uncertain.

Many residual potato herbicides persist in soil and there are restrictions on the choice of crops which can be grown after their use, particularly after early potatoes when the interval between application and the following crop may be relatively short, or in a dry summer when the risk of damage from soil residues increases. Lettuce is very sensitive to linuron; lettuce and dwarf French beans are sensitive to metribuzin residues and winter cereals may also be affected although ploughing reduces the likelihood of damage. In the same calendar year, only winter wheat should follow potatoes treated with rimsulfuron.

Weed control in potatoes grown organically is easier than in many other crops and is with harrows, ridgers pre-emergence and inter-row cultivations post-emergence. Problem weeds are likely to be perennial species, e.g. creeping thistle.

Potato haulm destruction

Some potato crops are left to senesce naturally, but most potato haulm is destroyed by mechanical and/or chemical means for a number of reasons: to kill weeds in order to facilitate mechanical harvesting; to encourage tuber skins to set before the planned harvest date, which is essential before potatoes are put into store; to restrict tuber size; to reduce spread of tuber blight (*Phytophthera infestans*) and *Erwinia* spp. from foliage to tubers; and to prevent aphid-borne virus in seed crops. Chemical desiccants are preferred, particularly in seed crops, to prevent the spread of *Erwinia* spp. Sulphuric acid (a 'commodity' chemical) requires special spraying equipment and is normally applied by contractors but it gives rapid, safe and complete desiccation and so for many growers it remains the desiccant of choice.

Diquat, glufosinate-ammonium and now carfentrazone-ethyl are alternatives to sulphuric acid. When applied to immature crops when the soil is dry and humidity high, diquat can translocate to tubers and cause vascular discolouration and in extreme circumstances tuber rotting, beginning at the stolon end. Such damage can be prevented if product label instructions are followed. Glufosinate-ammonium can translocate and damage 'eyes' in seed potatoes, so the label prohibits its use on these crops. In addition, on extremely wet soils glufosinate-ammonium can cause a tuber rot beginning in the 'eye'. It is likely that this is caused by leaching of the active ingredient through the soil to the 'eye' of the potato, rather than by translocation from foliage to tuber. Again, the directions on the label are written in such a way as to prevent such problems from occurring.

Sequences of desiccants are now becoming much more common in the drive to desiccate haulm rapidly and completely. Such sequences may involve diquat followed by sulphuric acid, sulphuric acid followed by sulphuric acid, or diquat followed by glufosinate-ammonium. Some crops are mechanically flailed first and then treated with one of the desiccants. A small minority of crops are desiccated with a hot plate heated with a propane/butane gas burner.

In organic crops, desiccation is based on flailing alone. More complete desiccation is likely to be achieved by flailing followed by propane gas burning.

Volunteer potatoes

In other crops, potatoes as volunteers often present a major weed problem. They can be aggressive and damaging weeds and potato 'berries' or stem can contaminate peas and green beans, for example. The persistence of potatoes as volunteers is a special problem for the seed-potato producer and can lead to crop rejection since there are only limited tolerances in the certification regulations for non-crop varieties of potato. Plants must be hand-rogued if possible. The volunteers act as reservoirs for potato pests and diseases, posing a threat to the health of both neighbouring crops and subsequent crops grown in the same field.

The majority of volunteers originate from tubers, usually small, which are not removed from the field by potato harvesters, but some may be derived from true seed. Experience shows that volunteer potatoes can survive through six-year rotations at least. It is now possible to develop glyphosate-tolerant varieties of potato; if these were introduced, the consequences of these as volunteers could be devastating.

Control of volunteer tubers

This has been the topic of considerable research which has shown that there is still no easy way of eliminating the problem. Sowing competitive crops such as winter cereals immediately after potatoes minimises daughter tuber production. Tuber numbers are reduced by the effects of frost, small mammals and birds, and therefore ploughing aids tuber survival. However, a non-ploughing regime may conflict with a requirement to plough after certain potato herbicides have been used to avoid risk of damage to succeeding crops, or with ploughing that is needed to correct soil damage after a wet harvest.

Treatment of the growing potato crop with maleic hydrazide will normally reduce the multiplication potential of tuber-derived volunteers, but this option is not available to the producer of seed and for some ware markets.

Modified harvesting machines were developed that could collect or crush small tubers, but they were not adopted by the industry because of high cost and unsuitability for use on stony soils.

Herbicides do not usually give high levels of volunteer control. The most effective herbicide for the control of volunteer potatoes is glyphosate; good control of daughter tubers has been achieved when application is made to plants with well-developed foliage. Glyphosate used before harvesting of cereals is thus reasonably successful if the potatoes have not senesced at this time. Selective application of glyphosate with roller or wick applicators is only suitable where there is sufficient height differential between the target weed and crop. This is possible in carrots and dwarf French beans, but sometimes unacceptable levels of crop damage are reported. The method is rarely used in sugar beet because the height differential is usually insufficient.

A number of post-emergence herbicides used in sugar beet, such as clopyralid and triflusulfuron-methyl, suppress potato volunteers, particularly where sequential applications or tank-mixes of different products are used. Repeat doses of salt + non-ionic wetter are also effective. Some temporary shoot suppression has been achieved with metoxuron in carrots and fomesafen + wetter in dwarf French beans. Fluroxypyr in cereals can be applied at a late cereal growth stage and has achieved some reduction in daughter tuber viability, although effectiveness may be related to potato growth stage at the time of application.

Leguminous crops

An expansion of the area of peas and beans followed the introduction of an EEC subsidy in 1978 for home-produced protein for animal feed and resulted in increased development of varieties and pesticides for these crops. In 1993 support was changed to an area payment with peas and beans sold at world market prices. In future the area of protein crops grown will depend on profitability relative to cereals, a demand for a GM-free source of vegetable protein and farmer perception of the importance of a spring break crop. World prices are low and inputs, including herbicide costs, need to be managed with care. Yield response must cover the cost of herbicide plus application at least, but other factors such as the effect of weeds on harvesting and prevention of weed seed return are also important.

As a result of lack of support by agrochemical companies for many active ingredients in the EC review including fomesafen, terbutryn and cyanazine, it is possible that products which have become the mainstay for weed control in peas will no longer be available after 2003, and perhaps only bentazone, and MCPB, MCPA and pendimethalin (dried peas only), will survive. This situation will create major challenges for the pea industry.

Peas for dry harvest

Peas harvested at dry seed stage (combining peas) are grown mainly for animal feed but there are markets for micronising for pet food, for canning or dry packet sales for human consumption and also for pigeon feed. There was some interest in the autumn-sown crop but the area is now negligible. Peas are also grown on a small area for ensiling at the green immature stage for animal feed.

Peas are drilled as early as possible in spring. They have slow initial growth and experiments have shown that early removal of weeds before peas are at the three-node growth stage prevents yield loss but herbicide application four weeks later is uneconomic. Nearly all varieties are semi-leafless and have a more open plant habit than conventional leaved types, but the newer ones are tall, stiff-strawed and resistant to lodging and are thus better able to suppress weeds.

Weeds seriously reduce pea yields and tall species such as wild-oats which shade the crop are particularly damaging. Black bindweed and cleavers can overrun a lodged pea crop. Volunteer oilseed rape in peas has become a widespread and persistent problem. Infestations of cleavers appear to have increased in recent years, possibly because of the use of reduced dose rates of cleaver herbicides in cereals. All these species interfere with harvesting and if they are not controlled a desiccant is needed, which adds to production costs. Peas are harvested in August and, with the exception of wild-oats, these weeds will not usually set mature seeds.

Peas are sown on a row width of 200 mm or less, without mechanical weeding, so the grower relies entirely on herbicides to control weeds. One herbicide application for broad-leaved weeds is sometimes sufficient for this short-season crop. A few small-seeded varieties grown for pigeon feed/forage are sensitive to some herbicides and there may be label exclusions. Residual herbicides are applied before the emergence of weed and peas, where soil type and seedbed conditions are suitable. They are ineffective at an economic rate on organic soils, and none has a recommendation for use on sands. Terbutryn/terbuthylazine controls most species and annual meadow-grass; fomesafen/terbutryn or pendimethalin formulations control volunteer oilseed rape as well. None of these is effective on cleavers but a new active ingredient, clomazone, is now approved and will be useful in tank-mix to widen the weed spectrum to include this weed. Black-bindweed is late germinating and sometimes escapes control with residual herbicides.

Foliar-acting post-emergence herbicides are used as a follow-up treatment for weeds which escape pre-emergence control, or alone as an alternative where dry or cloddy seedbeds would reduce residual activity or where rape and cleavers are the main weeds. The timing of application is precise and related to the pea growth stage. The contact-acting herbicides rely on adequate epicuticular wax on pea leaves for selectivity. Peas can be assessed for leaf wax by retention of crystal (methyl) violet dye. The 'hormone' herbicides must be applied before the enclosed-bud stage of the peas to avoid flower abortion. A post-emergence tank-mix of pendimethalin + bentazone is used very early, between the one- and before the three-node stage; tank-mixes of bentazone/MCPB plus cyanazine and of cyanazine plus MCPB/MCPA are applied later, but cyanazine was not supported in the EC review and will be lost. MCPB controls a limited spectrum but is useful for docks and thistles. Herbicides which suppress volunteer potatoes are not safe to peas.

Annual grasses, wild-oats, spring-germinating blackgrass and volunteer cereals are controlled with post-emergence graminicides but the high doses required for common couch are uneconomic. Couch is best eradicated with an autumn application of glyphosate before sowing peas, or before harvesting the pea crop (but not for seed crops).

Desiccation of dry harvest peas with diquat to kill off green weeds which might cause harvesting difficulties is a useful harvesting aid.

There are no guidelines as yet for organic production, but peas at both early and late growth stages are able to withstand weeding with flexible tines and a tall, stiff-strawed variety will suppress weeds.

Vining and picking peas

Peas are grown as a vegetable harvested at the green immature seed stage for quick-freezing or canning (vining peas) or they are hand-picked and sold loose in pods for the fresh market (picking peas). Although varieties may differ, for the purpose of agrochemical application they are considered to be the same. A very small area of edible podded (mange tout or sugar snap) peas is grown in the UK; because a different part of the plant is eaten, these are considered separately. There are very few herbicide recommendations, and only a few can be extrapolated from dwarf French beans. The growing season for peas is short, about four months. Sowing programmes ensure continuity of supply, and for vining peas begin in February and finish in early June. Peas are grown on a range of soil types but heavy, poorly drained land is unsuitable.

Some semi-leafless erect varieties are grown, but most are conventionally leaved and weak-strawed, and lodge at an early stage. Therefore weeds grow through the crop canopy. The vining pea crop is harvested with specialist pea harvesters which shell the peas in the field and, although weeds are less likely to interfere with this operation, weedy contaminants such as flower or seed heads of creeping thistles, mayweeds, common poppy and fragments of oilseed rape are difficult to separate from produce. Some mayweeds also cause taints. Land previously cropped with linseed is avoided because of the risk of contamination with capsules from volunteers. Vining pea crops are sometimes rejected to avoid risk of poisonous berries of black nightshade or volunteer potatoes in produce. A very high standard of weed control is therefore necessary in the processed crop to avoid quality problems in the factory. In hand-picked peas contaminants are not a problem but, as with other crops, thistles and nettles are unpleasant for pickers.

Weed control is with herbicides, and there are guidelines for growers to reduce volunteer problems with integrated crop management (ICM). Patches of thistles are treated before cropping with peas. With the exception of pendimethalin, herbicides have similar recommendations to those for dry harvested peas. However pea varieties differ in their reaction to herbicides, and some are sensitive. The principles involved remain unclear, but the small-seeded 'petits pois' types are more sensitive to some residual materials and varieties with pale, soft, leafy growth are often damaged by contact-acting post-emergence herbicides. Only fomesafen/terbutryn appears to be safe to all varieties.

Most crops are treated with a residual herbicide applied pre-emergence, except for late sowings where dry conditions would reduce activity. Fomesafen/terbutryn is used where volunteer rape is anticipated. A follow-up post-emergence application of MCPB can suppress thistles. Volunteer potato foliage cannot be suppressed in peas but prevention of berry formation is vital and only an application of cyanazine + MCPB/MCPA, as late as possible (but before 'flower-bud emerged' stage), will achieve this.

Herbicide damage suffered by pea crops can delay maturity. This disrupts vining pea harvesting and may result in by-passing the crop, while in picking peas it interrupts continuity of supply. Flower-bud abortion caused by late herbicide application must therefore be avoided.

Peas are particularly sensitive to soil or crop residues of clopyralid applied in other crops or for spot treatment of areas of thistles.

Peas are also extremely sensitive to sulfonylurea herbicides used in other crops, e.g. triflusulfuron, and drift or sprayer contamination will cause initial yellowing of the crop followed by severe stunting and multi-tillering of plants which remain green but set tiny pods and seeds. Field beans are also affected by sulfonylureas.

Where fomesafen is used in peas (or beans) there are restrictions on following crops: only cereals can be grown in the same calendar year and land must be ploughed and thoroughly mixed.

Organic pea production is negligible at present in the UK and, on the row widths currently used, flexible tine weeding is the only mechanical option, otherwise, weeds germinating just before the peas emerge are removed with flame weeders.

Field beans (*Vicia faba*)

Field beans are grown in autumn (winter beans) on heavier soils where it is difficult to achieve a suitable spring seedbed. Although some crops are drilled, the large seeds are often broadcast and then shallowly ploughed in. Spring-sown field beans (spring beans) are grown on a wide range of soils and drilled as early as possible, usually on 200 mm rows. Field beans are tall with an indeterminate growth habit. Most winter bean varieties are very long-strawed and thus compete well with weeds, although the low plant density reduces the competitive effect early in the season. Weed populations on heavy, cloddy seedbeds are usually low; some data suggest that weeds in winter beans often do not pose a threat to yield and significant expenditure on weed control is rarely warranted. Weeds are more damaging in the spring crop, particularly if high populations compete for moisture.

Weed problems are related to the germination periods of various species: cleavers and blackgrass are an increasing problem in autumn-sown beans, although some may germinate in spring as well; black-bindweed affects the spring-sown crop. Black-bindweed and cleavers grow above the crop canopy and cause lodging and harvesting difficulties, black-bindweed and volunteer rape are still green at harvest and require desiccation, and cleavers and blackgrass senesce and set seed. It is therefore considered important to control these species. Common couch is often associated with field beans grown on heavy soils, and volunteer potatoes can be a problem on lighter ones.

Most of the winter bean crop is treated with simazine, a cheap soil-applied residual herbicide which controls many broad-leaved weeds and some grasses. Whether simazine will achieve Annex 1 status in the EC review remains to be seen. Ploughing in the seed ensures adequate depth protection of more than 80 mm and the surface is usually levelled before autumn herbicide application. Alternatively, early harrowing in spring to encourage tillering of the crop and to remove weeds can be done before treatment with simazine, which is safe to the emerged bean crop. Simazine is a persistent material and must be applied before the end of February to avoid any soil residues affecting the following cereal crop. Cleavers and volunteer oilseed rape are not susceptible to the triazines registered for the crop. There is now a SOLA for pendimethalin applied pre-emergence of winter beans which will help to control cleavers, but there is a risk of crop damage on soils prone to waterlogging. It is likely to be used in tank-mix with simazine. Cereal drills used to sow spring field beans cannot sow deeply enough to allow safe use of simazine, although some farm-adapted machinery can do so. Pre-emergence herbicides containing fomesafen and pendimethalin control oilseed rape. The dose rate of pendimethalin is too low to be effective in the spring on cleavers. Clomazone, a new pre-emergence herbicide for cleavers and a few other broad-leaved species, used in a tank-mix will be very helpful.

The field bean crop is heavily reliant on residual herbicides for broad-leaved weed control but there are no recommendations for highly organic soils or sands, and if activity is reduced under dry soil conditions and weeds escape control, a selective foliar-acting herbicide may be needed post-emergence. Unfortunately beans are very susceptible to most of these materials; leaf wax is insufficient to avoid scorch by most contact-acting herbicides and translocated 'hormones' cause severe epinasty. There is no means of suppressing creeping thistle or volunteer potatoes. Bentazone, which has a limited weed spectrum, is the only option and is used mainly for cleavers and volunteer oilseed rape. However, it is relatively expensive and reduced dose rates are sometimes used in an attempt to cut costs, so the cleavers may be stunted. Nevertheless, cleavers still sets seeds which re-infest the following crop.

There are several herbicide recommendations for controlling annual grass weeds in winter beans, including tri-allate granules, propyzamide applied before crop emergence, and carbetamex pre- or post-emergence of weeds. So far blackgrass resistance to these has not been found. Propyzamide and carbetamex also control some broad-leaved species. Propyzamide must be applied before the end of December: it persists in the soil and mould-board ploughing is needed before a following cereal crop is sown. Several post-emergence graminicides are now approved for use in beans, with cycloxydim + oil the most widely used. The best and cheapest means of eradicating common couch is with glyphosate applied either pre-harvest in the previous cereal crop, or in autumn before sowing, or pre-harvest of beans (not seed crops). It is not economic to use the high dose of graminicide required for perennial grasses in beans, and the annual dose rate will suppress couch.

Where weeds are likely to interfere with harvesting, diquat is used to desiccate green weedy material.

Field beans sown on wide rows can be grown successfully without herbicides, by using mechanical weeding. Where herbicides are permitted, simazine is a cheaper method of weed removal.

Broad beans (*Vicia faba* var. *major*)

The majority of broad beans are sown in spring for processing, but the area has declined. Broad beans for fresh market are sown mainly in spring but some are overwintered to achieve an early harvest. Many varieties of broad beans are large-seeded; seed costs are high so they are sown with specialist precision drills on row widths of 300–450 mm.

Spring-sown broad beans grow rapidly and achieve better weed suppression than most vegetable crops. In machine-harvested crops for processing, the main weed problems are volunteer oilseed rape and potatoes because weedy contaminants affect produce quality. Black-bindweed causes severe difficulties where direct harvesting is attempted because it entwines round the picking reel. Thistles are unpleasant for hand-pickers in the fresh market crop.

A residual pre-emergence herbicide is used in most crops, usually terbutryn/terbuthylazine, or if there is a risk of oilseed rape volunteers, fomesafen/terbutryn. A shallow drilling depth precludes the safe use of simazine and some small-seeded broad beans are sensitive. A post-emergence herbicide may be needed; many have been tested but, as for field beans, the only safe option is bentazone. If it is applied in hot weather (> 21°C) leaf blackening can occur and one variety is sensitive to bentazone. Bentazone is mainly used to control oilseed rape volunteers and, although the addition of oil would improve efficacy, it is not recommended because of a greatly reduced safety margin.

Weed control without herbicides can be achieved on the wide row crop with mechanical weeding.

Dwarf French (green) beans

Dwarf French (green) beans (*Phaseolus vulgaris*) are grown for quick-freezing, canning and the fresh market. Much of the crop is mechanically harvested. The area for processing has declined. Green beans for processing are precision-sown with pneumatic drills which currently operate on a minimum row width of 300 mm, but many are still sown on 400 mm rows, whereas the optimum for yield is 200 mm or less. Sowing programmes, beginning in mid-May outdoors, are used to achieve continuity of supply.

The crop does not produce much foliage until fairly late in the season, so competition against weeds is not very effective in the early stage of growth. The crop plants are short and many weed species as well as volunteer potatoes can grow above the canopy and cause substantial yield reduction. Woody-stemmed and bushy weeds such as redshank and fat-hen interfere with machine-harvesting. The presence of poisonous weedy contaminants in machine-harvested produce can result in crop rejection; stalks of volunteer potatoes and black nightshade (which germinates in late June) are frequent problems.

A herbicide programme is needed. Three applications of different herbicides were used in the past, but there are now very few herbicides available for the crop. Successive weed flushes can be encouraged to germinate by cultivations before sowing. During the sowing period soil conditions are often dry and a stale seedbed technique is used with a non-selective or contact-acting herbicide applied before sowing, to kill emerged weeds. Trifluralin can be sprayed and incorporated before sowing; moisture loss is reduced by drilling immediately and the use of press wheels on the drill unit, or by rolling. Trifluralin can reduce or delay crop emergence in cold, wet weather and is often used. The residual pre-emergence herbicide monolinuron was once more popular, but is no longer manufactured. Chlorthal-dimethyl now has a SOLA for pre-emergence use. Fomesafen, which has contact and residual activity, is applied early after emergence when the beans are at the 'simple leaf' stage. It is effective on most weed species, but chickweed and annual meadow-grass are resistant. However, fomesafen was not supported in the EC review. This can be followed by bentazone, applied from the '$1\frac{1}{2}$ trifoliate leaf' stage of the crop.

Volunteer potatoes are a particular problem; shoots which emerge before the green beans are sown can be treated with glyphosate, and after emergence a split-dose programme of fomesafen with wetter applied early to small potato shoots, and then to shoots emerging later, achieves good suppression. If there is sufficient height differential between crop and potato, selective application of glyphosate with a weed wiper can be effective but slow. Potatoes are often removed by hand-hoeing or pulling.

Annual and perennial grasses, except for annual meadow-grass, can be controlled with cycloxydim after emergence.

Some varieties of green beans are sensitive to herbicides, but this used to be more of a problem with monolinuron.

Weeds can be controlled with mechanical weeders where crops are sown on wide rows, but green beans are shallow-rooting and may be damaged; soil build-up round the stems may interfere with mechanical harvesting.

Runner beans (*Phaseolus coccineus*)

Runner beans are grown on sheltered sites in order to avoid wind damage and to produce early crops which fetch a premium. Thus there may be little or no crop rotation. Early crops are sown either through polythene covers or covered after sowing until the small plant stage. The single or double rows of climbing plants are supported by canes or a semi-permanent system of strings laced between horizontal wires. Paths between the rows allow access for hand-picking and machine cultivators. Runner beans at early stages of growth are particularly susceptible to weed competition and, later, weeds interfere with hand-picking. The growing season is long, and residual herbicides lack the persistence required to control weeds throughout.

Successive weed flushes can be encouraged to germinate by cultivations before sowing. Black polythene will reduce weed emergence. If there is a danger of the seedbed drying out, a stale seedbed technique is used, and weeds emerging before the crop is sown are killed with a non-selective herbicide.

Following the withdrawal of some herbicides for runner beans there are now very few available so effective weed control has become extremely difficult. There are label recommendations for trifluralin applied pre-sowing and incorporated into the soil, and also for chlorthal-dimethyl, which has a wide margin of crop safety, controls black nightshade but is costly.

There are SOLAs for pre-emergence use of chlorpropham/fenuron, for simazine and pendimethalin which permit use on crops under cover and also for control of black nightshade. Pendimethalin should be used at low dose rates and simazine lacks safety in runner beans. Sometimes a tank-mix of some of these, e.g. pendimethalin + chlorthal-dimethyl or chlorpropham/fenuron, is used. If soil conditions are dry under polythene cover, the efficacy of residual herbicide is reduced.

The only post-emergence herbicide with a label recommendation is bentazone, and when crop covers are removed it must not be applied too soon or the soft growth will be damaged. The system of growing runner beans with support means that treatments are difficult to apply and hand-weeding is often performed as an alternative. Although there is an extrapolated post-emergence use for fomesafen, this can be very phytotoxic to runner beans.

Fenuron and fomesafen were not supported in the EC review of active ingredients.

Growing runner beans without herbicides could involve sowing through black polythene mulch, followed by hand-weeding.

'New' leguminous crops

There has been some interest in winter- and spring-sown sweet lupins, soya and lentils, which are all eligible for EU area subsidy. Soya is classified as an oilseed in the UK.

Winter-sown lupins at early growth stages are poor competitors with weeds. The 12-month growing season and lack of tolerance to nearly all post-emergence herbicides, including those for peas and beans, are major problems. An extrapolation from combining peas and field beans is permitted, and clomazone (the new pre-emergence herbicide for cleavers control) will be useful. Diflufenican, used for lupins in Australia, could solve the problem but residue studies would need to be undertaken. It is easier to control weeds in the spring-sown crop.

Soyabean is sown in spring, it is also uncompetitive at early stages and tall weeds will smother the crop. However, at present a programme of pre- and post-emergence herbicides is effective: linuron followed by fomesafen early post-emergence, and then bentazone (all having SOLAs). The future loss of fomesafen will affect prospects for the crop.

Winter sown lentils could be promising but there are no label recommendations, no extrapolations from another crop are permitted and they are very sensitive to post-emergence herbicides. Their slow initial growth and short plant habit mean that they are vulnerable to weed competition. They are grown at high plant density and hand-weeding is extremely difficult.

Carrots and related crops

Carrots

Carrots are grown mainly for the fresh market, with outgrades or defective roots used for stockfeed. The area grown for canning has declined; some are processed or grown for ready prepared packs/meals. Carrots are grown on sandy soils so that roots can develop without restriction and be well shaped. Mechanical stone separation is often needed. A few carrots are grown on organic soils. Soil blowing can occur on both soil types; where this is likely, barley is sown between rows as a shelter crop and removed later with a graminicide.

The production system depends on the market outlet, time of harvest and harvester used. All carrots are drilled with pneumatic precision drills. Crops are sown on wide rows (350 mm) where top-lifting harvesters are used until late October; baby carrots for processing are drilled at high populations often with twin- or triple-line coulters on a four-row bed system and are share-lifted from the end of August onwards. Early fresh-market carrots are seeded at low density in late autumn or winter and the beds are covered in clear film plastic or non-woven fleece. Main-season and late crops are drilled from February to May for harvest from August and into the following year, when they may be protected in the field by covering with deep straw or black polythene.

In carrots a high standard of weed control is needed to avoid yield loss and to maintain quality and desired size grade, particularly for baby carrots. Volunteer potatoes are particularly competitive. Knotgrass, annual meadow-grass and common couch interfere with mechanical harvesting, and tall species such as fat-hen and mayweeds are a nuisance where top-lifting harvesters are employed. Nettles are unpleasant where carrots are hand-pulled for bunching. Species which are closely related to carrots are difficult to control.

Carrots were the first vegetable crop in which effective chemical weed control was achieved with mineral oils in the late 1940s. Since then carrots have been treated with herbicides, and there are several label recommendations. Control is achieved with a combination of pre- and post-emergence herbicides and occasionally machine- or hand-hoeing or hand-weeding. Repeat low-dose programmes and tank-mixes are usually necessary to cover the weed spectrum. In later drillings, weed pressure can be minimised by adoption of a stale seedbed technique, and this also helps to control fool's parsley and wild mignonette (*Reseda lutea*), which occur on sandy soils. Carrots for early market must not suffer any damage likely to delay maturity; therefore post-emergence herbicides are avoided if possible.

Linuron pre- or post-emergence has been widely used for many years in carrots to control annual meadow-grass and broad-leaved weeds; pendimethalin, prometryn (useful for control of fumitory) and chlorpropham also have residual activity; trifluralin (incorporated before sowing) is rarely used. Linuron + metoxuron tank-mix is the standard for post-emergence control of broad-leaved weeds, and chlorpropham/pentanochlor is expensive but useful for knotgrass control. Mayweeds are controlled post-emergence with metoxuron, fool's parsley with ioxynil (SOLA), and fool's parsley and wild mignonette with metribuzin (SOLA). Unfortunately, prometryn, pentanachlor and metoxuron were not supported in the EC review. Volunteer potatoes are usually hand-pulled. Hemlock (*Conium maculatum*) and wild carrot cannot be controlled with herbicides and must be removed by machine topping, or with inter-row hoes.

Annual and perennial grasses, and cereals as volunteers or where they are sown as cover to prevent damage from soil blows, are removed with a range of post-emergence graminicides.

Carrots grown under plastic cover are more difficult to keep weed-free because these conditions favour emergence and growth of weeds as well as the crop. Isoxaben has a SOLA for pre-emergence application to carrots grown under cover but no other herbicide has a label recommendation, although residual herbicides are used after drilling and before covering the crop. The cover is removed when seedlings are well developed in April or May; however, contact herbicides that are applied when growth is soft may damage the crop as well as the weed.

Carrots are grown on soils prone to leaching, and care must be taken that no herbicides appear as major pollutants of groundwater.

It is possible to grow carrots organically; stale seedbeds and flame-weeding followed by hand-weeding when the carrots are at early growth stages, and black polythene cover, are all methods that are employed. Established organic growers use weeding platforms that carry up to eight people lying prone and weeding as the platform is towed down the beds.

Celery

Early and late 'self-blanching' celery harvested from July to November is grown at high density on narrow rows from transplants mainly on organic, but sometimes on mineral soils. Very few crops are drilled and celery is seldom grown in trenches now. Irrigation is essential. Self-blanching celery has a short growing season.

Weed numbers are reduced with a stale seedbed technique. Use of a contact herbicide before planting may necessitate fewer herbicide applications to the crop and is essential on organic soils. A few of the herbicides used in carrots are suitable for celery.

After transplants have established, a residual/contact-acting herbicide is applied, such as chlorpropham alone, chlorpropham/pentanochlor or linuron (up to the two rough leaves stage only) or prometryn after the two rough leaves stage. Prometryn is widely used in protected celery because it is safe to the crop. Prometryn and pentanachlor were not supported in the EC review and only chlorpropham and linuron remain. There will be a little residual activity on organic soils. If weed control is achieved during the first six weeks, celery is then very competitive and no further treatment is required. Hand-weeding is rarely needed, except for specific problems. There are no means of controlling grass weeds now that diclofop-methyl is no longer available. The morphology of the celery plant is different from that of other crop species and larger amounts of pesticides may be retained, resulting in higher levels of residues. There are therefore no minor-use extrapolations to celery and the number of label recommendations is likely to remain small.

In organically grown celery, weed numbers are reduced by cultivations and a stale seedbed before transplanting followed by hand-weeding or hoeing.

Parsnips

Parsnips are grown on a bed system on sandy soils where roots can develop without restriction and mechanical stone separation may be needed. They are sown in autumn and covered in clear plastic film for early harvest from late June, and in spring from February to early June for harvest from August to April. Seed is precision-drilled, and higher populations are sown for the autumn crop. Parsnips are slow to emerge, their growing season is long and suppression of weeds is poor.

Rotations with a five-year break avoid build-up of difficult species. Weed problems in parsnips are similar to those in carrots. Locations where wild parsnip (*Pastinaca sativa*) is found in fields should be avoided for parsnip seed crops because they can hybridise with the cultivated crop and may also contaminate the harvested seed.

Weeds are controlled with herbicides developed for the carrot crop. The larger parsnip leaf retains more herbicide than carrots and parsnips are less tolerant of post-emergence herbicides. For crop safety, herbicides are applied at half-dose rates and/or at a more advanced growth stage than carrots, but bearing in mind harvest intervals. There are several herbicides with label recommendations for parsnips, including trifluralin pendimethalin, linuron, and pentanochlor post-emergence and several graminicides. Herbicides with a label approval for carrots that can be extrapolated for use in parsnips include metoxuron and prometryn.

Any cultivations must be done with care, to avoid damage to parsnip crowns. Weed control methods for organic production are with inter-row brush weeding and hand-weeding within the row.

Onions and related crops

Onions

Bulb onions

These account for over 80% of the onions grown in the UK. The vast majority of the crop is spring-sown/planted in February/March. Approximately 70% of the spring-sown onion crop is direct-drilled; the remaining 30% is planted as sets. Onion sets grow much more rapidly than drilled crops and are therefore generally at a more advanced stage than the weed, thus aiding herbicide selectivity. Weed control in sets is also generally cheaper than drilled, as initially higher rates of the residual herbicides pendimethalin and chloridazon can be more safely used. A small proportion of the crop is grown overwinter, almost exclusively from October-planted sets.

Onions are relatively slow-growing, have an upright foliage habit and do not form a dense canopy, making them very susceptible to weed competition. Poor weed control can therefore result in significant yield and quality loss. Heavy weed infestations also encourage pests such as cutworms and thrips and restrict airflow through the crop, leading to increased incidence of fungal diseases. Weeds may also hinder bulb ripening.

The main problem weeds are mayweeds, fat-hen, *Polygonum* spp., fumitory, volunteer potatoes and annual meadow-grass. Volunteer cereals are often a problem in overwintered crops, which are usually established after cereals.

Rotations and cultural practices should be chosen to minimise ‘volunteers’ in onions, which should not be grown in the year after potatoes.

Studies have indicated that the ‘critical period’ (the time the crop needs to be weed-free to prevent yield loss) for drilled bulb onions is a one to two-week period, seven to nine weeks after 50% emergence.

After drilling/planting, residual herbicides are applied: typically on mineral soils a combination of pendimethalin and propachlor, and on organic soils chlorpropham plus propachlor, are generally used. As the spring-established crops are slow to emerge, typically taking three to four weeks, weeds appearing before crop emergence are controlled with a non-selective herbicide based on glyphosate or paraquat.

Post-emergence applications of propachlor, pendimethalin (SOLA) and chloridazon (SOLA) are commonly used in conjunction with a contact herbicide, such as ioxynil, up to the second true leaf stage.

Choice of post-emergence contact herbicides depends upon the weed species present, efficacy and crop safety. Ioxynil is still the mainstay of onion control programmes, and is usually used in combination with other contact herbicides such as cyanazine for control of *Polygonum* spp., fluroxypyr (SOLA) for control of volunteer potatoes and cleavers, bentazone (SOLA) for control of mayweeds and clopyralid for thistles and mayweeds. Prometryn is widely used on onions for control of weed species commonly found on sandy soils, e.g. fumitory. Cyanazine, sodium monochloroacetate and prometryn will be lost as a result of the EC review. All post-emergence contact herbicide programmes are based on the principle of repeat low dose applications.

Grass weeds and volunteer cereals are controlled using post-emergence graminicides such as cycloxydim (bulb and salad onions) or fluazifop-p-butyl or propaquizafop (bulb only); tepraloxydim (bulb onions) offers a better solution to the increasing problem of annual meadow-grass. Graminicides are also used to kill shelter rows of barley drilled between rows of (drilled) onions where peat or sand soil blowing causes crop injury or loss.

Care should be taken with all post-emergence herbicide applications, particularly before the three true leaf stage, as their crop safety depends entirely on an adequate level of leaf wax. Leaf wax levels can be determined using crystal violet dye. If weather conditions are unfavourable for wax development or there has been damage or abrasion to the foliage, severe crop damage can result from herbicide application.

Salad onions

Salad onions account for around 20% of the UK onion crop. Crops are sown in succession from February to September. As they occupy the ground for a much shorter time than bulb onions and are grown at higher plant densities, weed control may be less of a problem. Weed control strategy is similar to that for bulb onions, but particular care should be taken to observe harvest intervals and avoid herbicide damage to the leaf which can render the produce unmarketable.

In organic onion crops weed control is with mechanical (hoeing and harrowing) and thermal methods. Flame weeding is used to kill emerged weeds before crop emergence. Selective post-emergence flame weeding has been used in onions to control small broad-leaved weeds, although grasses seem to be relatively tolerant to this treatment. As onions have a basal growing point and waxy leaves, they tend to tolerate flaming better than many weeds. Black polythene mulches are also used.

Leeks

Most leek crops are drilled to a stand, but early and late crops are often transplanted. Cultivations which ridge up soil along crop rows are frequently used to provide a better blanch and this also reduces the number of herbicides required. The spring-drilled crop, like onions, is in the ground for a long period and some weed species can re-infest the current crop. Leeks suffer from similar weed problems to onions and the critical period for weed control is at the one- to three-leaf stage of the crop.

Onion herbicides are used, but since leeks have a larger 'funnel' type of leaf and there is less 'run-off' they are more sensitive to the post-emergence herbicides. Leeks may also collect more pesticide residues than onions and this restricts the use of some chemicals. Drilled leeks are slow to emerge and a contact-acting herbicide kills weeds which emerge before the crop. A pre-emergence residual herbicide is used and post-emergence herbicides are applied early, from one to three true leaf stage of the crop, often as split doses. Prometryn, usually in a tank mix with ioxynil can be applied at a later stage and is used on about 90% of the leek crop. The eventual loss of prometryn will cause problems for leek growers.

Organic growers are more likely to grow leeks from bare root transplants (apart from those drilled in a seedbed). In transplanted and drilled leeks, brush weeders, steerage hoes and Lilliston cultivators are suitable for cultivating between rows and throw soil into rows to bury small weeds. In organic crops of drilled leeks, delayed sowing a few days after seedbed preparation may allow weeds to emerge significantly ahead of the crop and flame weeding is then used. Another flame weeding can be done up to the 'crook' stage of development (as in onions), before the risk of damage is too great.

Lettuce

During the 1990s the range of lettuces grown widened and it now includes crisp (iceberg), cos, endive (escarole and frisée), Little Gem, butterhead and continental types such as Lollo Rossa and oakleaf. Recently 'baby leaf' lettuce has become popular. Outdoor lettuce is grown from transplants in blocks or modules. The early lettuce crop is frequently grown under the protection of fleece or polythene perforated with small holes. Woven fleece has superseded polythene in most cases to avoid scorching the lettuce when there are sudden rises in temperature.

Continuous lettuce production is carefully planned and any crop check or maturity delay caused by weed competition or herbicide must be avoided. There is zero tolerance of weeds whose seed contaminants reduce product quality or hinder hand-harvesting. Lettuce is a short-term crop so several crops are grown on the same land in a single season. No herbicide with a label recommendation for lettuce controls mayweed or groundsel (*Senecio vulgaris*), although propachlor has a SOLA and helps to control Compositae. Crop rotation would reduce this problem, but many factors influence field lettuce production and often breaks of only one year are achieved. Block/module transplants of early-maturing varieties do not usually suffer from severe weed infestation but in later-maturing and in all drilled crops problems can be acute.

Continuous cropping on the same land and the short-term crop are limiting factors; thus there are few herbicide options. Propyzamide, a widely used pre-emergence residual herbicide, propachlor pre- or post-emergence and pendimethalin (SOLA) all have SOLAs for use under covers but none of these can be used on transplants. Chlorpropham can also be used pre-emergence on drilled lettuce, but not on sands or very light soils, and it can be damaging. Tank-mixes of propachlor with propyzamide or chlorpropham at reduced dose rates are also used. Trifluralin soil incorporated before drilling or transplanting is less safe to the crop and is seldom used.

The risk of damage to tender leaves prevents the use of later herbicide applications and often mechanical methods or hand-weeding supplement chemical weed control, usually to remove weed species not controlled by the herbicides. Propyzamide has a six-week harvest interval and it is persistent in the soil, so care should be taken in respect of following crops. A soil fumigant is sometimes used to kill weed seeds, soil-borne diseases and insects and also in the production of 'baby leaf' crops. Dazomet granules are incorporated in the soil, which is then covered with polythene.

In 'baby leaf' lettuce, steam sterilisation is also used before planting. This method is successful, but slow at 40–100 h/ha. The use of a dry heat system which sterilises 2–5 ha/day has also been investigated.

Where lettuces are grown organically without pesticides, weeds are controlled with mechanical tine, brush or 'A'-blade weeders or by hand-weeding (typically two passes) where lettuces are grown on a 250 mm row spacing. Another option is to grow organic lettuce on close spacing to crowd out weeds, and to hand-weed.

Most of the herbicides are safe to the types of lettuce mentioned, but new varieties of speciality lettuce are constantly being introduced and there may be differences in tolerance. Propachlor causes a growth check but the delay in maturity is usually 'built into' the sequence of croppings.

There are extrapolations from the few herbicides approved for use in lettuce to several other minor but important uses: spinach, 'baby leaf brassicas', lamb's lettuce, frisée, radicchio, escarole, cress and leaf herbs. If approvals in lettuce are not maintained these other crops would be affected.

Linseed and flax (*Linum usitatissimum*)

Linseed occupies the larger area and is grown for oilseed for industrial oil and cake for animal feed, and flax is grown for fibre production. Linseed has become less profitable since the EU support for the crop has decreased and the area has declined. There has been some interest in winter linseed where trifluralin was found to be damaging, but most of the crop is spring-drilled on narrow rows. Linseed is fine-leaved and has poor ground cover at early growth stages and is a poor competitor with weeds, but the high population densities effectively smother weeds later.

Herbicides approved for oilseed rape may be used in linseed and flax. However, the same herbicides are not necessarily recommended. For example, MCPA is used for linseed but causes unacceptable distortion of fibre and loss of quality of flax. Broad-leaved weed control is based on foliage-applied herbicides: bentazone, MCPA, metsulfuron-methyl and clopyralid for thistle and some perennial weeds and amidosulfuron for cleavers control.

The linseed crop is desiccated mainly with diquat. Glyphosate is used for pre-harvest retting in flax.

Linseed and flax are shallow rooting and grown on narrow rows, and crops are not mechanically weeded.

Maize and sweetcorn

In the UK, the area of maize grown for ensilage as cattle feed increased in the early 1990s but in 2001 it was static at about 110 000 ha, and little is grown for grain. A small area of sweetcorn is grown for human consumption. Forage maize varieties are more vigorous and competitive with weeds than sweetcorn. Maize is drilled in late April/May for harvest in late August and September; sweetcorn is drilled or transplanted. Both crops are sown on very wide rows (750 mm) to suit most seed drills or for hand-picking sweetcorn.

Maize and sweetcorn are slow-growing initially when temperatures are low and they seldom form a complete canopy before the end of July. Spring-emerging annual weeds can smother them at early growth stages and perennial species, particularly common couch, can cause suppression. Even when mature the canopy allows light penetration and weed growth beneath it. In the UK, most of the sweetcorn and half the forage maize area is grown repeatedly, without crop rotation, on the same sheltered field and repeated use of atrazine may lead to a build-up of black nightshade, which it does not control.

Broad-leaved and grass weeds are controlled by residual herbicide atrazine, usually pre-emergence, but it also has foliar activity and is sometimes applied early post-emergence. However, strains of annual meadow-grass or groundsel have become resistant to triazines. Where maize or sweetcorn has been grown continuously a tank-mix of atrazine + pendimethalin is used pre-emergence.

To protect water, atrazine now has restrictions on permitted use: the total maximum dose rate is now 1500 g active ingredient (a.i.)/ha, and the high dose rate for common couch is no longer approved. Decisions on whether atrazine and simazine are to achieve Annex 1 status in the EC review are yet to be made. Simazine (maize and sweetcorn) also has restricted use to protect water. Cyanazine (maize and sweetcorn) is a less persistent alternative and controls annual meadow-grass and broad-leaved weeds; pendimethalin alone, which can be used for maize, and there is a SOLA for sweetcorn or crops under cover; pendimethalin/cyanazine (for forage maize only); and these may be used in tank-mix with atrazine. Bromoxynil is now widely used for sites with black nightshade problems and general broad-leaved weeds, but there is a risk of scorch; therefore timing and weather conditions are critical. Bromoxynil/prosulfuron (maize) is safer to the crop. There are several other post-emergence options to solve most weed problems: pyridate (maize and sweetcorn) for black nightshade and cleavers; fluroxypyr (maize), also used for cleavers and docks; clopyralid (maize and sweetcorn) for creeping thistles and mayweed; and lastly rimsulfuron (forage maize) which can be used on named varieties only, before the 'four collar' growth stage of the crop for some annual broad-leaved weeds.

Atrazine and simazine residues in the soil can affect subsequent crops if the interval is too short or the soil remains dry so that degradation is delayed. Where clopyralid is used there are restrictions on following with susceptible crops.

Genetically modified herbicide (glyphosate, or glufosinate)-tolerant maize is at field experiment stage in the UK. If accepted, weed control could be simplified. Maize and sweetcorn grown on wide rows can be mechanically weeded.

Guidelines for organic maize production suggest two to three passes of inter-row hoes and a possibility of flame weeding at 5 and 25 cm height, as maize is relatively heat-tolerant. Maize grown organically for forage is frequently undersown with clover, which suppresses weeds and builds up soil fertility.

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Chapter 20
Management of Aquatic Weeds

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Introduction

The control of nuisance vegetation in watercourses is often necessary to ensure adequate flood defence for surrounding land, to provide facilities for recreational sporting activity, to provide better angling environments, to aid navigation, on public health grounds, for industrial uses and to maintain adequate water supply and quality. In recent years, weed control for conservation has also become necessary to protect native habitats from invasion by alien, introduced or non-native species.

Aquatic weeds are different from terrestrial weeds in that they are usually a normal constituent part of the aquatic ecosystem. Aquatic plants become weeds when they grow to excess, becoming a nuisance in terms of blocking channels, reducing flow or preventing other normal uses of the waterbody. Several factors have contributed to a perceived increase in aquatic weed problems: the increased eutrophication of lowland waters in Europe from point and non-point sources, and increased urbanisation leading to increased storm-water run-off and demands for improved drainage capacity of fixed systems. In addition, increased urbanisation has resulted in an increase in the number of non-native species now considered as aquatic weeds, due primarily to escape of plants from domestic situations. The increased recreational pressure on enclosed inland waterways, such as canals, gravel pits and lakes, has also resulted in greater demands for aquatic plant management.

Over the last 50 years, there has been a dramatic change in the type of aquatic weed problem. Emergent weeds, such as reeds and rushes, and floating-leaved weeds, such as waterlilies, used to be the main problem. However, eutrophication since World War II, resulting from intensification of agriculture, increased urbanisation and consequent sewage treatment requirements, has resulted in a shift to problems caused by filamentous and blue-green (cyanobacterial) algal blooms.

The responsibility for managing aquatic weed problems lies with many different types of organisation. Internal Drainage Boards are the oldest example of water management authorities and operate mainly in agricultural areas of the UK. In other European countries, the responsibility may lie with riparian owners, local government or water boards. Weed problems along main rivers are usually managed by central government agencies; in England and Wales this is the Environment Agency, which also has a regulatory responsibility for other aspects of river function. Riparian owners may carry out weed control operations in main rivers if they require a higher standard of maintenance, e.g. for fishing, than may be considered necessary by the Agency, which primarily manages aquatic weeds for flood defence reasons. Government authorities usually have responsibility for fisheries and for maintaining water quality. They have legal powers to restrict the use of certain weed control techniques in controlled waters (all water directly connected to main rivers), and should be consulted before any weed control operation.

Types of aquatic weed

Although there are a large number of individual aquatic weed species, for the purposes of management they can be divided into four major groups.

Emergent plants

Emergent plants are rooted in the sediment at the margins of watercourses. They have stems and leaves which protrude above the water surface. Growth is often limited by increasing water depth, so this type of weed occurs most often along the edges of water. Common features of these plants are long narrow leaves and a height of between 1 and 3 m. Species include *Phragmites communis* (common reed), *Typha latifolia* (bulrush), *Schoenoplectus lacustris* (common club-rush), *Glyceria maxima* (reed sweet-grass) and *Sparganium erectum* (common bur-reed).

Smaller emergent and bankside plants, except grasses, tend to be broad-leaved weeds. These include *Rorippa nasturtium-aquaticum* (watercress), *Apium nodiflorum* (fool's watercress), *Berula erecta* (water parsnip) and others.

Other plants in this group are predominantly submerged, but may form different types of leaf when they become emergent due to lowered water levels, or grow above the water surface. These include some *Ranunculus* spp. (water crowfoots) and *Hippuris vulgaris* (mare's-tail).

Plants that grow on banks at or above the water line should be included in this group. Common weeds in this class include *Lythrum salicaria* (purple loosestrife), *Epilobium hirsutum* (greater willowherb) and *Phalaris arundinacea* (reed canary-grass).

A number of riparian weeds associated with watercourses can be included in this group. The dispersal of these species is furthered by flowing water. The alien invasive species *Fallopia japonica* (Japanese knotweed), *Heracleum mantegazzianum* (giant hogweed) and *Impatiens glandulifera* (Himalayan balsam) are included here.

Floating plants

Free-floating plants

This group includes many of the worst aquatic weeds, such as *Azolla* spp. (water fern), *Eichhornia crassipes* (water hyacinth), *Lemna* spp. (duckweeds), *Pistia stratiotes* (water lettuce) and *Salvinia molesta* (giant water fern), all of which have been found in the British Isles. They are characterised primarily by very rapid vegetative reproduction and spread.

Floating-leaved plants

This type of plant is characterised by being rooted in the sediment and forming floating leaves. Species such as *Hydrocotyle ranunculoides* (floating pennywort), which have leaves held above the water surface, may be rooted at the margins and form floating mats over the surface of the water. Plants rooted in deep water having floating leaves held flat on the surface include *Potamogeton natans* (broad-leaved pondweed), *Nuphar lutea* (yellow water-lily) and *Nymphaea alba* (white water-lily).

Other plants in this group are predominantly submerged, but may form different types of leaf, such as the 'rosette' leaves produced by *Callitriche* spp. (water starworts), when they reach the water surface.

Submerged plants

This group includes all submerged plants except algae. It can be divided into two sub-groups: those rooted in the sediment, such as *Elodea* spp. (waterweeds), *Myriophyllum spicatum* (spiked water-milfoil) and *Potamogeton pectinatus* (fennel pondweed); and those free-floating below the water, such as *Ceratophyllum demersum* (rigid hornwort) and *Lemna trisulca* (ivy-leaved duckweed).

Algae

Algae can be divided into two types for the purpose of control: the macrophytic types, including filamentous algae and charophytes; and the unicellular types, including 'pea-soup' algae and the cyanobacteria, or blue-green algae. Nuisance algae tend to grow best in nutrient-rich, still or slow-flowing water.

The biology and ecology of aquatic weeds

Seasonal growth and dispersal

Aquatic plants are usually a problem only during the summer months. Various forms of dieback or washout during autumn and winter ensure that very little aquatic vegetation is left to overwinter. However, several strategies are used by nuisance aquatic weeds to survive winter. These include seed production by annual riparian weeds and as an insurance policy by perennial submerged aquatic macrophytes. Others, e.g. *Potamogeton pectinatus*, fennel pondweed, produce turions (specialised leaf buds) tolerant of anoxic conditions. The majority of emergent macrophytes have dormant roots and rhizomes. Spore production is used by algae and the aquatic fern *Azolla*, and others can overwinter as intact plants, e.g. *Callitriche* spp. and *Crassula helmsii*.

Aquatic weed growth usually starts when mean diurnal water temperature rises above 6°C; it is normally a week to a few weeks behind terrestrial plant growth. However, growth is rapid once started and stem elongation in *Ranunculus* spp. can produce 6 m of growth before flowering. Flowering is usually initiated by shortening day length, so the majority of aquatic plants flower in or after the last week in June in temperate areas of the Northern Hemisphere.

Stem fragmentation followed by vegetative reproduction is the most common form of dispersal within water systems; seed production is not considered important for maintaining weed populations. However, establishment of new weed populations is most likely to derive from establishment of seeds. Birds, animals, machinery, boats and human can also spread viable fragments of weeds to new sites.

Factors influencing plant distribution

The main factors governing individual aquatic plant distribution are primarily physical and chemical. Physical factors are influenced by the local geography and geology. These factors can interact to produce a range of characteristic aquatic habitats in which different species will tend to dominate.

Depth

The maximum depth at which freshwater aquatic plants can grow is governed by the availability of light, oxygen and carbon dioxide. In deep lakes, stratification often occurs in the summer; it is uncommon to find extensive growths of submerged aquatic plants below the thermocline in such systems. Oxygen and carbon dioxide are supplied from the atmosphere and from equilibrium reactions in water and sediment. Oxygen is re-supplied by diffusion from the atmosphere and so submerged plants with high respiratory requirements tend to be restricted to shallow or flowing water. Light intensity and quality change with depth, also affecting aquatic plant growth.

Rate of flow

Some plants with intrinsic high metabolic rates, such as *Ranunculus* spp., are adapted to fast-flowing water where diffusion boundary layers are small and nutrient uptake and gas exchange are relatively rapid. Others, such as *Nuphar* and other floating-leaved species, are most often found in still water. Floating leaves allow direct exchange of gases with the atmosphere, and although metabolic rates may be similar, a different strategy is utilised.

Light

Light intensity and light quality change with depth. As a general guide, higher plant photosynthesis ceases at about 1% of surface incident light intensity. Light quality changes by selective absorption of red light. Water plants growing at depth tend to have different light absorption pigments and are most often red in colour, i.e. they strongly absorb blue light.

Sediment type

Sediment type is a major factor determining the distribution of aquatic plants. Nutrient rich silts and muds are most often associated with aquatic weed problems.

pH

pH determines the chemical speciation of dissolved inorganic carbon and nitrogen in water, and can affect which species of plant are able to grow. Plants unable to assimilate bicarbonate ions are unable to grow above pH 8.2. Alkalinity is linked to pH, with high-alkalinity water most likely to have high pH values. High-alkalinity water also tends to be linked with increased aquatic weed productivity.

Nutrient status

The availability of nutrients affects the distribution of algae and of floating and submerged plants that absorb some, or all, of their nutrient requirements from the water. The most important of these nutrients are nitrate and phosphate, but trace elements and micronutrients also have an effect.

Characteristics of nuisance plants

Growth rate

Species which have extremely fast growth rates tend to become greater problems than other species. For example, duckweed and *Azolla* spp. can double their biomass in under four days in good conditions.

Morphology

Species that produce dense masses of vegetation impede the flow of water. Others have rigid stems which may impede boat traffic, interfere with access to the water and trap detritus, causing the formation of temporary dams which may cause flooding.

Dispersal strategies

Plants that produce new plants by fragmentation are also very effective aquatic weeds. Often, mechanical control has been responsible for increases in the distribution of these species in watercourses.

Toxicity and taint

Some plants are toxic to animals and others taint potable waters. Blue-green algae produce toxins which can kill fish and other animals and also impart an unpleasant taste to drinking water.

Control methods

Factors affecting choice

There are a number of factors that influence the choice of weed management technique, including the cost of control. These factors are related to the uses of the water and the specific landscape situation of the waterbody. Often, a compromise between weed control efficacy and other considerations must be made.

Type of control

In some cases it is not desirable to attempt complete eradication of the weed population and localised control is preferable. Selective control can be either by type of species or by area, e.g. clearing swims for anglers. Total control may be required where flood defence is an issue, or where non-indigenous species are present. Temporary alleviation of a weed problem is sometimes possible by frequent mechanical control during the season.

Use of the water

Certain weed control practices may not be compatible with the use of the water. The most obvious of these is when water is abstracted for drinking-water supplies downstream of an intended herbicide application site. The limit of 0.1 $\mu g/l^1$ for individual pesticides set by the EU Drinking Water Directive imposes strict requirements on the distance between the site of application and the abstraction point. This distance is affected by dilution and flow rate.

Human and livestock safety

This includes direct toxicity of herbicides to operators and water users, increases in turbidity due to stirring up of sediments, and unpleasant odours from rotting vegetation or herbicide residues in water. The safety of farm and other animals could be compromised by direct toxicity of the herbicide, or, as is more likely, by its increasing the palatability of treated poisonous plants.

Irrigation

The hazards to adjacent crops that should be considered arise through irrigation with water containing pesticides, spray drift at the time of application, and the spread of weeds such as *Phragmites australis* into crop land when dredged spoil is deposited onto land adjacent to watercourses.

Industry

Industrial processes requiring water may be affected by weed blocking intake sluices, or by the presence of pesticides in water.

Environmental impacts

In general, the more effective a weed clearance operation, the greater the environmental impact. Deoxygenation of water, affecting fish, can occur when large volumes of cut weeds are allowed to rot in situ. The number of invertebrates removed by mechanical control is estimated to be approximately 1 million/m^3 of cut weed, and the number of vertebrates, mainly small fish, is estimated to be about 40/m^3 of weed removed. Care should be taken to avoid removing marginal vegetation during bird nesting times. Other indirect effects include destabilisation of banks by removal of plant cover, or by deposition of thick layers of cut vegetation on sloping banks.

Management options

Mechanical control

The following points should be considered when using mechanical weed control.

- Rafts of cut weed can drift downstream and block sluices, pumps, weirs and other water control structures
- Deoxygenation can occur if weed is left to rot in water, posing a risk to fish and invertebrate life
- Rapid regrowth of cut weeds often necessitates a late-season cut

In practice, the cost of mechanical control limits the frequency of the operation, so a compromise between weed control and cost is usually necessary.

Cutting

Cutting aquatic weeds can be achieved manually or by using machines; the choice of technique depends on the scale of the problem to be tackled. Cutting by hand and raking cut material onto banks is no longer used widely, although the majority of small drainage ditches used to be managed in this way. There is now a wide range of mechanical cutting boats and weed bucket attachments available for bank-based machines, but the principles of cutting and removing the cut weed remain unchanged. In general, the deeper the cut the longer weed control will last.

Timing of the cut is critical. Good control can be achieved by regular cutting throughout the growing season, but this may not be possible for operational reasons. Cutting submerged weeds before the end of June will require a further cut towards the end of the season, and regrowth during summer tends to be faster than initial growth rates. The timing of cutting emergent and bankside weeds is less critical, but care should be taken to avoid bird nesting seasons.

Weed boats are used to cut submerged weeds in relatively deep and wide watercourses, where large areas of weed require cutting. They usually have a front-mounted reciprocating cutting bar which can cut to a depth of about 1.5 m. The work rate is estimated to be approximately 1 km per day on a 10 m wide river. Cut weed requires removal from the water, either by a separate boat or by the action of a front rake on the cutting boat after cutting.

Bank-mounted equipment includes draglines, flail mowers and dredging equipment. The work rate for cutting buckets and weed rakes is, on average, about 500 m per day on wide rivers.

Harvesting

The use of aquatic weed harvesters combines the cutting and collecting operation, therefore reducing time and increasing efficiency. They are capable of cutting and/or collecting all types of weed, including filamentous algae and duckweeds, and depositing them at a collection point on the bank. The work rates for this type of equipment vary considerably with the density of weed and the distance travelled to offload the collected weed.

Uses for cut weed

There are a limited number of uses for cut weed; these include composting, reed for thatching, mulches, soil conditioners and cattle forage. The material has a low value and processing should be done locally in order to minimise costs.

Chemical control

Herbicides can be used to control a wide range of aquatic plants. They may be applied to emergent or surface-floating weeds by a foliar spray in much the same way as is recommended for land plants. Submerged weeds and algae are treated by adding the herbicide to the water to build up an effective concentration in the water. This method will also control some floating and emergent species. The chemicals currently used to control aquatic plants in the UK are listed in Table 20.1.

Consideration should be given to the effects of herbicide treatment on the function of the waterbody. This not only involves the direct toxicity of the chemical, but also indirect effects caused by decomposition of dead weeds. It is recommended that a proportion of the weed growth is retained to maintain a habitat for invertebrates, fish and other wildlife, and to stabilise the ecosystem. Vegetation left in situ will take up nutrients and help to prevent the growth of

Table 20.1 Herbicides suitable for control of major weed groups

	Herbicide							
	asulam	2,4-D amine	dichlobenil	diquat	diquat alginate	glyphosate	maleic hydrazide	terbutryn
Trees and shrubs on banks						✓		
Bracken and docks	✓			●		✓		
Broad-leaved weeds		✓	●	●		✓		
Grasses			●	●		✓	✓	
Reeds and sedges				●		✓		
Floating-leaved plants			✓	●	✓	✓		●
Free-floating plants		●		✓		✓		✓
Submerged plants		●	✓	✓	✓			✓
Submerged plants (flowing water)					✓			
Algae				✓	✓			✓

✓ Suitable for control.
● Short-term control, or some species within groups not susceptible.

algae. In order to minimise the effects of decomposing weed, herbicide labels have recommendations on treatment intervals which should be observed. It is normal for only 25% of an infested waterbody to be treated at one time, separated by the application interval. Consideration should be given to the irrigation interval when using herbicides in water. This is the period between application and the time when water is safe to use for irrigation of crops or watering of livestock.

Application methods

Application to foliage

Recommendations for the correct dose are made in the form of weight of product, or active ingredient, per hectare. Herbicides are usually applied by knapsack or boat-mounted sprayer equipment. The use of high-volume and low-pressure equipment delivering a coarse spray with a minimum of small droplets is advisable to reduce the risk of spray drift. Localised or selective control can be achieved by the appropriate choice of herbicides and by spraying only those plants required. Water velocity and quality do not affect the treatment, but in order to avoid a build-up of chemical in the water, it is normal to apply herbicides in an upstream direction.

Application to water

Recommendations usually refer to the theoretical concentration of active ingredient that would be achieved when the chemical has been evenly distributed throughout the waterbody, but before any adsorption or degradation has occurred. This is usually expressed as parts per million (ppm or mg/l^1 or g/m^3). Some formulations may be applied on a rate per surface area basis because they sink onto the weeds or mud.

The methods of application depend on the formulation. Herbicides should be spread as evenly as possible over the surface of the water. Granular formulations can be spread by hand using a suitable container, by a mechanical spreader or by using an air-assisted blower. Liquid formulations should be diluted and applied by sub-surface injection. This is usually achieved by trailing nozzles below the water as close to the top of the weedbed as possible, without disturbing the bottom sediment. Viscous gel formulations should be applied with specialised equipment.

Timing

Emergent and floating-leaved plants should be treated from mid-summer, when the leaves have formed fully. Annual weeds should be treated before flowers have set, to prevent production of seeds. Treatment of submerged weeds and algae is normally recommended in spring and early summer, when weeds are actively growing. Treatment of floating-leaved plants is usually more successful before the floating leaves have formed. Later in the season, when large biomasses of weed have developed, and particularly when the water is warm, there is a severe risk of deoxygenation of the water after control, caused by decomposition of the dead weed. This effect is particularly acute when using terbutryn, as the mode of action blocks photosynthesis very quickly but respiration continues.

Risks and safeguards

Aquatic herbicides are approved for use in or near water. Only those pesticides specifically approved for use in water can be used on aquatic plants in water. Pesticides specifically for the control of plants growing near water are also included here (e.g. asulam and maleic hydrazide). The approval is based on toxicological data and on an assessment of the risk of exposure to the herbicide. For all other pesticides, the LERAP scheme provides for a Local Environmental Risk Assessment for Pesticides. The scheme sets buffer zone distances from the top of the bank for all pesticides. The minimum buffer zone distance is 1 m. Several herbicides have statutory minimum buffer zone distances which can be reduced if precautions are taken. Precautions include reduction of dose and use of low-drift nozzles. The definition of 'near water' is between the edge of the water and the top of the bank.

An indirect hazard to fish may arise through possible effects on fauna that provide food for fish. These may be due to direct toxicity to invertebrates, or more likely to loss of habitat after weed control operations. However, loss of habitat can lead to increased predation by fish. These effects are temporary and should be set against the disadvantages of dominant weed species reducing the habitat structure for all aquatic fauna.

Before applying herbicides to water, operators should consult the *Guidelines for the Use of Herbicides on Weeds in or near Watercourses and Lakes* (MAFF, 1995), which gives guidance on the risks associated with application of herbicides to water. They should also consult the local authority responsible for prevention of water pollution, the Environment Agency, the Scottish Environmental Protection Agency or the Department of the Environment in Northern Ireland.

Biological control

The decline in the public acceptability of herbicide use in water, coupled with an increase of costs of mechanical control, has led to the development of several biological control agents for aquatic weeds.

Biological control has been successful in about 45% of the attempts made on aquatic weeds worldwide. It is essentially a management tool designed to maintain the level of a pest at a tolerable level in the community, without necessarily eradicating the weed species. It is a useful tool to employ in combination with other techniques such as mechanical or chemical control. The use of biomanipulation to restore the macrophyte communities of the Norfolk Broads is also a form of biological control. Exclusion or removal of zooplanktivorous fish from areas has resulted in increased grazing pressure on algae and restoration of clearwater conditions in which macrophytes have flourished.

Livestock

Horses, cows, goats and sheep can be used to graze marginal vegetation. Care should be taken to avoid excessive poaching of the banks (although some poached banks are a valuable habitat) and fencing is required to keep animals from straying.

Chinese grass carp and other fish

Herbivorous fish are most common in Asia and South America. One species, the Chinese grass carp, *Ctenopharyngodon idella*, is available for weed control in enclosed situations in the UK. Licences are required for the introduction of these fish and users should obtain them from the Environment Agency and DEFRA before introducing this species. Stocking densities vary, depending on the type and severity of the weed problem, but usually a density of between 75 and 150 kg/ha^1 will achieve adequate weed control. A comprehensive guide (Environment Agency R&D Note 53) to the use of grass carp for aquatic weed control is available from the Environment Agency in England and Wales. Bottom-feeding fish stir up sediment and create turbid conditions in which submerged macrophytes cannot grow. These fish species include primarily carp and bream.

Waterfowl

Waterfowl graze on some species of floating and submerged weed. However, when present in large numbers (e.g. swans on *Ranunculus*) they can cause significant losses of aquatic vegetation, which may not be desirable.

Pathogens and insects

Classical biological control is not widely practised in Europe, and not at all on aquatic and riparian weeds. Biological control agents survive only on their host species, meaning they cannot spread to ornamentals or related crop species. Most native plant species have a number of native host-specific pathogens or insect predators. There are effective biological control agents for many aquatic weed species (Table 20.2) established in other parts of the world, but none is used in Europe.

Environmental control

Environmental control is the technique of changing the environment, either temporarily or permanently, to reduce the suitability of the habitat for the target weed. This technique tends to shift the weed species to other plants, which may or may not be desirable depending on the ultimate use of the waterbody in question.

Table 20.2 Established biological control agents for aquatic weeds

Weed species	Biological control agent	Type	Region
Alternanthera philoxeroides	*Agasicles hygrophila*	Flea beetle	America
Azolla filiculoides	*Stenopelmus rufinasus*	Weevil	S. Africa
Eichhornia crassipes	*Neochetina eichhorniae*	Weevil	America, Africa, India
	Neochetina bruchi	Weevil	America, Africa, India
	Cercospora piapori	Fungus	Africa
	Alternaria eichhorniae	Fungus	Africa
Hydrilla verticillata	*Hydrellia pakistanae*	Insect	America
	Hydrellia sarahae	Insect	
	Hydrellia pakistanae	Insect	
	Hydrellia balciunasi	Insect	
	Mycoleptodiscus terrestris	Fungus	
	Plectosporium tabacinum	Fungus	
	Cricotopus lebetis	Midge	
Myriophyllum aquaticum	*Lysathia* sp.	Beetle	S. Africa
Myriophyllum spicatum	*Bagous subvittatus*	Insect	N. America
	Bagous myriophylli	Insect	
	Phytobius	Insect	
Salvinia molesta	*Cyrtobagous salviniae*	Weevil	Africa
	Neohydronomus affinis	Weevil	

Flow

Aquatic plants may be classified as riverine or lacustrine species. Although this division is not mutually exclusive, plants that tend to favour slow-flowing environments do not grow in faster-flowing water, and vice versa. Alterations to flow can have marked effects on the composition of the aquatic plant community.

Water chemistry

Reduction of the quantity of major plant nutrients entering water tends to reduce the biomass development of weed species, but not necessarily the species composition of the weed community. Diversion or further treatment of sewage effluent to remove excess phosphate has been effective in stabilising river communities by removing the dominance of filamentous algae. Nutrient release from sediments is a major source of supply for lakes and other slow-flowing watercourses, such as canals and drainage ditches. Even if all nutrients could be prevented from entering such systems, there would be sufficient nutrient supply in the sediment to provide for continued aquatic plant growth for over 100 years in most cases.

Shade

Shading submerged aquatic macrophytes can be an effective method of control, especially in sensitive areas such as Sites of Special Scientific Interest (SSSIs) and

Special Areas of Conservation (SACs) where chemical control is inappropriate. Shade can be produced by planting trees or shrubs on the banks of watercourses. However, this often interferes with access to the water and may not be appropriate in all situations. Opaque floating material can be used in still waters to achieve increased shading, although it must remain in place for at least four months to have a lasting effect. The use of dyes that absorb light at photosynthetic wavelengths is also widespread in amenity lakes and ponds. Increased turbidity from bottom-feeding fish also excludes light, as does the action of powered boats; these techniques are most effective in sluggish water where the sediment can remain suspended for long periods.

Burning

Emergent weeds, particularly the stiffer stemmed reeds, do not always collapse in the autumn and can form large masses of dead, standing material. In dry ditches and on banks this material can sometimes be burnt. This can be a useful way of reducing the bulk of plant material which might otherwise collapse during the winter and block channels. Burning can also be used to destroy cut material after drying. This is a good way of disposing of poisonous plants, some of which remain toxic after death but become palatable to livestock.

Alterations in water level

Exposure of part, or all, of the bed of a waterbody by lowering the water level has been used successfully to manage aquatic vegetation. Control is achieved either by dehydration of the vegetation or by exposure to low temperatures. The process is sometimes termed ‘drawdown’, or ‘dewatering’. It can also alter the character of the sediment, which may reduce weed growth. However, in deeper waterbodies, drawdown can allow weeds to establish in depths below their normal limit. Once established, they can grow up towards the surface, as the level is again raised, to remain in the higher light intensity. In these situations, drawdown can spread a weed problem into areas which would normally remain weed-free.

Comparison of treatments

Some indication of the relative effectiveness of treatments can be seen in Table 20.3. This is not a definitive guide for every situation and expert advice should be sought before application of any technique to a particular weed problem, in order to optimise efficacy and minimise costs.

Other methods of control

Many other techniques for controlling aquatic vegetation have been tried which do not fit closely into any of the previous categories. These include:

Table 20.3 Relative efficacy of management options*

	Weed type					
	Emergent		Floating-leaved		Submerged	
Management option	Narrow-leaved	Broad-leaved	Rooted	Free-floating	Rooted	Algae
Mechanical						
Hand-cutting	●	●	●	✖	●	✖
Flail mower	●	●	✖	✖	✖	✖
Weed bucket	●	●	●	●	●	●
Weed boat	●	●	●	●	●	✖
Harvester	●	●	●	●	●	●
Dredger	✓	✓	✓	✖	✓	●
Chemical						
Foliar application	✓	✓	✓	●	✖	✖
Applied to water	✖	✖	✓	✓	✓	✓
Biological						
Livestock	●	●	✖	●	●	✖
Waterfowl	✖	✖	✖	✓	●	●
Fish	✖	✖	✓	✓	✓	✓
Insects and pathogens	●	●	●	✓	✓	●
Biomanipulation	✖	✖	✖	✖	✖	✓
Environmental						
Shade	●	●	●	●	●	●
Nutrient manipulation	✖	✖	✖	●	●	●

* The benefits assigned to each technique are for general guidance only and the results obtained may be modified by specific site conditions.
✓ Effective control lasting at least one season.
● Moderate benefit only, or control lasting less than one season.
✖ No useful effect.

(1) the use of lasers to control emergent or floating weeds and ultrasound vibrations which can disrupt cells of submerged plants;
(2) floating oil films which cause floating weeds to sink;
(3) increasing wave action which submerges floating weeds and increases turbidity, thus suppressing submerged vegetation.

There are also several biological control agents, including crayfish, other invertebrates and wildfowl, which have been effective against some weeds. Most of these have been tested in tropical or sub-tropical conditions; at present, the grass carp is the most effective biological control agent in the more temperate regions. Some of the more effective alternative treatments are outlined below.

Magnetic treatment of flowing water

The use of magnetic water treatment devices has been shown to affect the growth of algae. This is thought to be due to interference with the uptake and storage of calcium in algal cells. This treatment is most effective in closed recirculating systems.

Ultrasound

Ultrasonic devices are used widely in Europe to disrupt cells, mainly of algae and biofilm bacteria, in water storage reservoirs where herbicides cannot be used.

Miscellaneous treatments

There are a number of alternative treatments for water that affect the nutrient concentration, and therefore the nutrient availability to aquatic plants. Most of these involve precipitation of phosphate in an insoluble form.

Legislation

Several Acts of Parliament and European Directives are concerned with the management of water, the use of herbicides and the movement and introduction of fish. Some of those relating to chemicals are outlined in Chapter 7, in the DEFRA (formerly MAFF) publication *Guidelines for the Use of Herbicides on Weeds in or near Watercourses and Lakes* and the DEFRA/HSE annual publications *Pesticides 20xx*, where 20*xx* is the current year. The use of herbicides for aquatic weed control is covered under the Food and Environment Protection Act 1985 (FEPA), Control Of Pesticides Regulations 1986 (as amended) (COPR) and the Plant Protection Products Regulations 1995, in addition to other supporting legislation. The Biocides Directive, administered by the Health and Safety Executive, also covers the use of some herbicides and other registered products for aquatic weed control. There are many sources of information on herbicide use available to the public, but the first source of information should be the Pesticides Safety Directorate.

Reference

MAFF. (1995). *Guidelines for the Use of Herbicides on Weeds in or near Watercourses and Lakes*. PB2289. HMSO: London.

Chapter 21
Where is Weed Management Going?

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Introduction

Rural policy sets the context within which growers have to take decisions on cropping systems. EU policy is having three main effects: enhanced concern for the environment, reduced prices for farm produce and re-registration of agrochemicals. Agenda 2000 has placed the environment explicitly into the Common Agricultural Policy, which puts constraints on the farm practices. The support prices of many products are being reduced, and therefore reduction in the costs of production is a financial imperative for growers. The re-registration of agrochemicals is compulsory but costly and, not surprisingly, many off-patent chemicals are not being re-registered, thus reducing considerably the herbicide options available to growers. All these topics have been considered in chapters of this book. The policy context sets weed management along a route which involves achieving sufficiently clean crops to attain an economic yield without adversely affecting the environment.

How are weed scientists and technologists responding to these challenges? How will growers respond?

Weed biology

Inevitably, most of the work of weed biologists has been focused on those species which have a large effect. We have little information on the biology of many weed species. Nevertheless, we increasingly need this information in order to develop any management interventions we propose. We also need the information to incorporate into decision-support systems (DSSs) for if the information is incomplete we should not expect effective solutions to be proposed.

Much of the work of weed biologists has concentrated on the behaviour of propagules, the agents of spread, whether seeds or vegetative parts. Knowing how the seed bank operates is crucial if we are to integrate soil management and weed management. We have learnt much about the dynamics of seed banks in both time and in space, but the predictive models often have large errors attached.

Another important aspect of weed biology has been the investigation of competitive effects. Unless we know what impact particular weed species can have on the yields of crop species, we cannot decide the priorities for weed management systems. We need to address the questions ‘what do we control?’, ‘what do we leave?’ and ‘how do we decide?’.

Supporting technology

Herbicide discovery and delivery

The available herbicides work by disrupting plant growth at relatively few points in the complicated metabolism and physiology of the whole plant. We do need to continue the search for new mechanisms of herbicide action, and then develop effective, environmentally benign, commercial herbicides. However, the costs of herbicide discovery, patenting and registration are high, so companies are concentrating their search on compounds which will be effective for a few crops which have large markets: wheat, maize, soybean, cotton. Uses for other crops will have to be developed secondarily.

We are using technology to develop new methods of delivering herbicide to the plant in a safe way. Packaging technology and application technology both work towards increased operator and environmental safety and reduction of the scope for making mistakes.

Non-herbicidal techniques

Because we are likely to have fewer herbicides available and in response to consumer and society concerns, we are revisiting pre-herbicide techniques of managing weeds. Mechanical weed control techniques are likely to be far more important in low-area crops as herbicides become unavailable. Biological control is also receiving heightened interest. There is a clear trend towards Integrated Farm Management (IFM) and this includes Integrated Weed Management (IWM). Here the aim is to turn from responsive-mode herbicide use to a more thoughtful approach, taking account of all the crop management decisions in order to minimise the use of costly inputs. This approach is promoted in the UK by LEAF (Linking Environment and Farming), and by other organisations elsewhere in Europe. A further driver of change towards IWM is the increasing sale of many crops on contract direct to supermarkets. Many supermarket chains have set their own ‘quality standards’ of production which limit the compounds that can be used, and when. Consumers undoubtedly find the multiplicity of terms on food labels confusing; one welcome development is the LEAF Marque, a common standard which many of the supermarkets are accepting as an alternative to their own individual schemes.

Decision support

There is a clear trend towards helping growers take informed decisions. Information technology can put 'an expert in every farm office'. Decision-support systems have the potential to do this but can only be as good as the knowledge contained within them. Thus, DSSs need to have encyclopaedias of herbicides and of weeds. However, the difficult task is to build the software that uses all the information about the site, the crop, past and predicted future weather and the grower's local experience to propose a solution which is effective. This is being done (e.g. in the UK through DESSAC; see Chapter 15) and ten years hence we should see this system being widely adopted.

Incorporating information on varieties

Each year plant breeders go to great efforts to produce new varieties of crops. For new varieties to be registered they must be distinct, uniform and of use in agriculture. Much information is available to growers from the range of associations which evaluate released varieties. In the UK these organisations include the National Institute of Agricultural Botany, the Arable Research Centres, and groups dedicated to specific crops or products, e.g. potatoes or sugar. Again, this information is available and should form part of the strategy for any grower in developing cropping systems and contributing to integrated weed management.

Knowledge of the local climate and the yield potential of the site are important factors to consider. Decisions on the intended sowing time and position in a crop rotation influence the choice of varieties, which should be competitive and suited to local conditions. Information is available to assist the choice of appropriate varieties.

Weed management in practice

So what do growers actually do? In the past, some growers have been rather lazy and taken the fire-brigade approach to weed control – I will wait and see what weeds come up and then I will ask an advisor or a salesman what to do. Fortunately, such growers are becoming rare. Modern crop management demands a much more thoughtful approach. The financial imperative to drive down costs is forcing us to take a hard look at costly inputs of fertilizer and agrochemicals. Options for reducing applications include highly targeted delivery or alternative non-chemical methods. This approach has environmental benefits, as can the specification of crop protection by wholesaler supermarket chains and their developing acceptance of the LEAF Marque as a common alternative. This is not to say that we have all the answers. Because we develop new cropping systems, so we expect new weeds to develop prominence in them, creating new management challenges. This is even before we consider any changes which might result from climate change.

Not all growers may implement all the options available. The use of DSSs and high-technology systems of accurate and targeted herbicide application comes with significant capital and recurrent costs. In regions where mixed farming is the norm, or on farms where crops are grown mainly for livestock feed, economics may preclude their use. On such farms the options for effective weed management, performed in an environmentally benign manner, become more limited. An increasing proportion of growers choose to reject the option of herbicide use, preferring to produce organic crops. This approach has the same challenges but a reduced set of weapons. In a recent survey of organic farmers in the USA, weed management was identified as the top research priority. This is in recognition of the importance of weeds in reducing crop yield (and quality) and the interest in developing new weed management techniques. Similarly, organic growers in regions of the UK rated their weed management as generally effective, but few thought it to be very effective. These grower opinions highlight the need to develop more effective weed management techniques, particularly if this perceived barrier to conversion to organic systems of production is to be removed.

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