CHAPTER 9

WEED MANAGEMENT

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Attainment of profitable crops is necessarily related to the costs of the inputs to reduce competition from weeds and the reduction in yield or product quality due to that competition. The Grains Research and Development Corporation indicated in 2001 that such costs in Australia are of the order of $3.3 billion. The cost effectiveness of herbicides, their ease of use and efficacy in most cases have resulted in an industry highly dependent on herbicides to the extent that herbicide resistance threatens the viability of the herbicide-based farming systems. This reliance upon one weed management technique needs to be replaced by a more strategic approach whereby weeds are managed over many years rather than year-by-year. It involves using other methods including appropriate tillage, herbicides, good crop husbandry and key management practices elsewhere in the rotation in a coordinated program often referred to as integrated weed management (IWM).

Weed Distribution

Weeds are not distributed evenly across a field but, rather, occur in discrete patches. These patches may merge over time or in particular seasons such that there is a continuum, but density varies across that continuum. Such patches will be the result of an initial invasion of a weed seed or seeds through

- wind, water or animals including excreta deposits
- conserved fodder
- field equipment and other vehicles
- contamination of crop or pasture seed.

Such resulting plant (or plants) will endeavour to complete its lifecycle and seed will be set and shed in close proximity to its origin. Subsequent germination events will produce a patch. There is a reasonable relationship between the occurrence of a patch from one year to the next. The patch shape and extent will be modified according to physical operations in the field through cultivation and harvest operations as well as herbicide applications. For example, it would be expected that the patch would extend in the direction of the travel of a harvester if the weed seed is harvested and then deposited out the back of the machine. Other weeds tend to shatter before harvest whilst others have a habit of growth that tends to avoid harvest and hence are less affected by the harvest process.

This spatial variability represents a challenge for modern day farmers. In the past the presence of weeds resulted in attention to the whole field – either by cultivation or herbicide application. Increasingly, however, technology is allowing the patchiness to be addressed. Remote sensing technologies incorporating global positioning systems can at particular times provide a map of weed distributions. Such maps can be used to program boom sprays to apply chemical in specified areas of the field, a process called precision weed management. In a fallow situation it is possible for the spray apparatus to detect green material such that the application mechanism can be triggered. The minimalist position is that, based on the maps, a farmer may treat only parts of the field.

PREVENTION IS BETTER THAN CURE

As a matter of principle it is better to prevent or reduce a problem in advance than be confronted with a major challenge in-crop. Therefore, issues of hygiene become important as does the need to prevent or reduce weed seed set.

Hygiene

Simple procedures, often ignored by farmers, include the following:

- preventing introduction of weeds through contamination in seed or hay brought onto the property. This applies particularly where the weed species is not present on the farm or field. Often resistant weeds are also introduced through this means. Obtaining appropriate sources of seed should be a key priority;
- preventing the introduction of weed seed onto the property with livestock. Weed seeds can adhere to livestock due to characteristics of the seed (e.g. clover burr) or seed head, or may be readily retained as vegetable matter contamination in wool. By shearing new sheep prior to release onto the property, or by purchasing freshly shorn sheep, the risk of weed seed spread can be reduced;
- quarantining livestock brought onto the property to ensure any weed seeds in the digestive tract are expelled in holding yards, rather than across the property. It has been shown (Andrews, 1995; Edwards *et al*., 1998; Stanton *et al*., 2002) that livestock can excrete viable seeds for up to a week after ingestion;
- observing hygiene procedures with equipment. This applies particularly at harvest time as crop harvesters move from field to field and, in the case of contractors, from district to district. Heylin (2002) showed that water plantain (*Alisma plantago-aquatica*), for example, readily adhered to both the inside and outside of the rice header. This emphasises the importance of harvesting clean fields first and meticulous cleaning of equipment before it enters clean fields. Table 9.1 shows the rapidity of spread of water plantain in the Finley district of NSW. This is likely to be due to machinery spread or water transport or some combination;
- regular control of weeds in irrigation supply channels so that weed introductions to irrigated fields and bays are minimised.

Table 9.1 The increase in incidence of water plantain on farms in the Finley district (Lacy, 2001)

Farmer Group	% farmers per group with water plantain	
	January 1999	January 2001
Tongaboo	88	100
Mayrung	23	45
Coree	69	93
Logie Brae	100	100
Tuppal	36	100

Jerilderie	67	100
Tocumwal	84	100
Blighty	23	28
Oaklands	46	95
Berrigan	60	73
Mean	60	83

Seedbank Management

Weed populations generally emanate from seeds produced in the previous seasons. It follows, therefore, that any operations that limit the production of seeds will reduce the number of weed seedlings that need to be controlled in-crop. Confounding factors include weed seed dormancy mechanisms that provide species longevity in the seed bank over a few to many years. Several years of close attention can be cancelled by one year's inattention to recruitment prevention. The complementary approach is to encourage germination from the seed bank to enable control, thereby reducing the seed bank's capability for establishing future high populations.

The pasture phase provides an opportunity to put into effect seed bank decline measures. It becomes important that the pasture is vigorous to provide competition to the undesirable species. Choice of pasture species can be critical, depending on the weed species to be controlled, as can soil fertility management.

In subterranean clover pasture, for example, phosphate application can contribute to an early invasion of annual grasses (Kohn, 1974, 1975; Ayers *et al*., 1977a) such as annual ryegrass (*Lolium rigidum*), barley grass (*Hordeum leporinum*) and silvergrass (*Vulpia* spp.), which are important weeds of cereal crops and hosts for a number of cereal diseases (Butler, 1961; Rovira, 1987). Managing such swards in the final year or two of the phase is critical to minimise the carryover of these diseases (Kidd *et al*., 1992; McNish, 1989) and weed populations.

Management options for annual grass control (as reviewed by Leys, 1990) include:

- spray-topping of annual grass species at early seed set with paraquat, paraquat/diquat mix or glyphosate to render the weed seed unviable (Pearce, 1973; Jones *et al*., 1984, Davidson, 1992). Timing of the spray, after anthesis but before seed maturation, is critical and seed set reduction of 70 to 95% may be expected depending on the evenness of the population. A prior grazing to ensure an even crop of seedheads followed by a post-spraying grazing is good practice. There is a risk of herbicide resistance developing in the weed populations to these chemical groups if there is a reliance upon these chemicals for pre-season knockdown weed control;
- pasture cleaning with simazine, paraquat or a simazine/paraquat mix during early winter (Leys and Plater, 1993). The regular use of simazine for this purpose increases the frequency of use of that chemical in the rotation where it is also used for weed control in crops such as lupins or triazine-tolerant canola. This

increases the risk of herbicide resistance developing in the weed populations to this chemical group;
- fodder conservation and heavy grazing at seed set. Where hay is involved, both conserved on site or purchased, it is important that mature seeds are not present as they represent a source of weed spread. Such hay needs to be harvested before seed set but not too much before as a second flush of seed heads may be produced;
- burning of grass residues, a process limited by seasonal fire regulations (Pearce and Holmes, 1976; Davidson, 1992).

The earlier the removal of grasses, however, the greater will be the control of the cereal diseases, since sufficient times and proper conditions must be allowed for microbial breakdown of the infested plant residues. The hot dry summers of the southern cropping areas are not conducive to microbial breakdown of the crop residues.

'Spray-graze' involves the use of low rates of phenoxy herbicides on young broadleaf weeds of rosette habit, such as Paterson's curse (*Echium plantagineum*) and capeweed (*Arctotheca calendula*) and minimises damage to the pasture legume. The chemical mobilises the weed plant sugars, making it sweeter, and distorts growth, such that the weed is more accessible to the grazing animal (Pearce, 1973). Grazing should take place 7-10 days post-spraying and very high stocking rates are needed to have the desired effect.

Livestock therefore provide a range of options for assisting in weed control. As previously described for weed introductions, there are precautions that need to be taken since they also represent a means of weed spread within a farm. For sheep, seeds can adhere to wool and be deposited in another field at a later time. Weed seed can also survive the gastro-intestinal track of livestock. Stanton *et al*. (2002) have shown that up to 4% of ingested annual ryegrass seed ingested by sheep is excreted in viable condition whilst up to 11% is excreted by cattle. Clean out takes 4 to 5 days so livestock should not be moved to "clean" areas without allowing up to a week for weed seed to be eliminated. Such precautions would also apply to grazing of crop stubbles where significant weed seed is available for animal consumption.

MECHANICAL WEED MANAGEMENT

A complementary approach to recruitment reduction of the seed bank is the active encouragement of weed seeds to germinate thus reducing the potential of the seed bank to provide an undesirable weed population in-crop. In an undisturbed seed bank the number of viable seeds will decline with time due to natural degradation factors. Such decline is often more than replaced by recruitment. Soil disturbance is a tool that can be used to manipulate the germination activity in the seed bank.

A technique, relatively uncommon in Australia, is the use of a mouldboard plough to bury weed seed at depth. This has been used effectively in European countries for the control of slender foxtail (*Alopecurus myosuroides*) (Moss, 1979). Its effectiveness, however, will be improved in species with a short-lived dormancy and an inability to emerge from depth. For species with a longer seed dormancy the risk is that such seeds are preserved until such time as a similar ploughing event brings them back to the soil surface and stimulates their germination. Various researchers in Australia have evaluated the practice for different species – Pearce (1973) for wild oats and spiny emex, Cheam (1987a, b) for spiny emex and brome grass and Gramshaw and Stern (1977) for annual ryegrass. Reeves and Smith (1975) also achieved useful control for annual ryegrass using a disc plough. Both mouldboard and disc ploughs are not encouraged for use in Australia due to their impacts on soil degradation and therefore are only a last resort.

During the process of seedbed preparation, tillage can be used to encourage or inhibit germination of different species. The principle here is to encourage weed germination in advance of crop sowing to enable a weed control measure, either herbicide or further tillage, to have a large impact on the weed population and reduce potential competition in crop.

The process of an autumn tickle, whereby a light cultivation with a scarifier provides surface cover for those weed seeds lying on the soil surface, is the most common. This process alters the light, temperature and moisture regime for the seed and increases the speed and uniformity of germination. The emerged population is then eradicated. This process will be successful where seed banks have been well-managed. Where very high populations of seeds exist in the seed bank, there may be more than one significant wave of emergence. The process of cultivation works well for annual ryegrass and has also been influential in encouraging the germination of fumitory (*Fumaria* spp) (Pratley, 1995). *Vulpia* spp react quite differently, preferring undisturbed seed beds as occurs in direct drilling. Cultivation will inhibit its germination and it is rarely a problem in cultivated seedbeds (Dillon and Forcella, 1984), including direct-drilled crops where a full soil disturbance occurs at sowing.

Table 9.2 Effect of lucerne ley on skeleton weed population, soil nitrate nitrogen, wheat yield and protein content on solonised brown soils of the Victorian Mallee (adapted from Wells, 1970)

Site	Skeleton weed population (plants/m^2)	Soil nitrate nitrogen 0-15 cm (ppm)	Wheat yield (t/ha)	Wheat protein (%)
Daalko				
Volunteer	479	6.1	1.03	6.4
Lucerne	17	11.0	1.57	13.7
Boulka				
Volunteer	263	2.2	0.10	10.5
Lucerne	71	11.0	0.72	12.4
Chillingollah				
Volunteer	372	5.1	0.35	12.4
Lucerne	19	8.3	1.32	12.7
Patchewollock				
Volunteer	372	1.7	0.17	9.0
Lucerne	46	5.2	1.25	12.1

Other weeds, however, adapt to cultivation. The most notable example in Australia is skeleton weed (*Chondrilla juncea*) which, as a perennial weed, has the capability to regenerate from plant fragments (McVean, 1965; Cutherbertson, 1967). The act of cultivation, particularly with disc ploughs, resulted in total crop losses in the 1930s due to this weed, and a pasture phase was introduced for its control. Lucerne pastures have been particularly effective in that role (Table 9.2). Silverleaf nightshade (*Solanum elaeagnifolium*), a deep-rooted summer perennial in south east Australia, also spreads by vegetative propagation induced by cultivation (Cuthbertson *et al*., 1976).

The alternative approach is to inhibit germination. For some species this means little or no seed bed disturbance. It needs to be recognised that weed seeds from the previous season are deposited on the soil surface. There they are exposed to environmental extremes of wetting and drying, light and dark as well as high and low temperatures. Those species inhibited by light will not germinate whereas dews and light showers of rain may encourage the process of germination to start but not finish because of desiccation. Surface seeds are also prone to scavenging by birds, livestock and ants thereby reducing significantly the numbers of viable seed. Such a tactic can work for species such as annual ryegrass and for fumitory. However, such an approach can be compromised by livestock treading the seed into the soil, particularly when the soil is wet, and by stubble retention systems where the presence of stubbles buffers the soil surface and therefore the seed from the extremes of temperature and moisture. However, it may also increase the energy required by the weed seedling to emerge above the stubble thereby weakening its competitive capability.

The decision on whether to till or not cannot be universal. It will vary with seasonal conditions and particularly with the weed species involved. Clearly, what works for one species does not necessarily work for another. Variety in approaches will restrict the system from favouring one species over another.

Tillage is also a useful tool for controlling seedlings. Full soil disturbance at sowing in a direct-drilled crop can assist with weed control by helping to remove larger weeds that are not controlled by herbicides due to their advanced size.

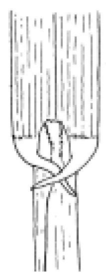
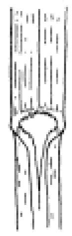
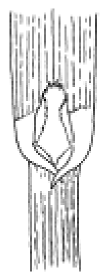
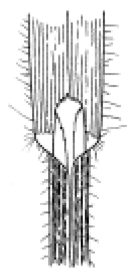
CHEMICAL WEED MANAGEMENT

Herbicides have been increasingly adopted by farmers for weed control since their availability in the late 1960s in the form then of the soil-incorporated grass herbicides. Relative to other costs of production, the direct costs to farmers of chemicals are significant, but benefits from their use are usually high. Australia's herbicide bill is well in excess of $400 million indicating that this technology is widely accepted by the farming community. Further, farmers are now very dependent on chemicals providing both non-selective and selective weed control to the extent that there has been much reduced reliance on alternative strategies such as cultivation in recent times. It is important to note that herbicides have allowed the development of conservation farming systems whereby damaging cultivation practices to a large extent have been replaced by herbicides.

This high dependency on herbicides continually raises questions in the community about the need and desirability of high levels of chemicals being introduced into the environment. Issues such as contamination of produce, pollution of water courses and groundwater and toxicity to non-target organisms, including humans, increase anxiety. Whilst it is not the purpose to canvass these issues here, they have been reviewed by Pratley *et al*. (1998) and Pimental (1997). Whilst herbicides can generally be considered relatively safe when appropriately handled, it remains an imperative for crop producers to ensure that any chemicals used are effective, and are applied within legislative constraints. On occasions, herbicides do not work and it is important that such occasions are rare so that ineffective chemical is not unnecessarily introduced into the environment. Some of the aspects of ensuring efficacy of herbicide use then are considered below.

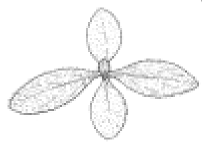
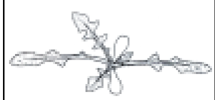
- *Correct identification* – From time to time, herbicides are applied to plant populations but do not work because the weeds have been incorrectly identified. A fundamental principle then is correct identification of the seedlings. A common mistake made in the winter cropping zones is silvergrass (*Vulpia* spp.) being mistaken for annual ryegrass, although the differences between the two species are observable and can be used in an indentification key to allow correct identification (Table 9.3). Herbicides effective on ryegrass are often ineffectual on silvergrass. The consequence is unnecessary chemical into the environment, a cash outlay for no return and a crop still full of competitive weeds. Similar keys, such as those published by Moerkerk and Barnett (1996) and Wilding *et al*. (1998), can be used to correctly identify broadleaf weed seedlings (Table 9.4). This allows the correct selective herbicide to be chosen and applied at the appropriate growth stage.

Table 9.3 An example guide to common grass weed species, based on seedling identification keys developed by Moerkerk (1998)

	annual ryegrass *Lolium rigidum*	silver grass *Vulpia bromoides*	wild oats *Avena fatua*	barley grass *Hordeum leporinum*	great brome grass *Bromus diandrus*
					
hairs	absent	absent	scattered	scattered	dense
auricle	long	short	absent	long	absent
ligule	wide membrane	short membrane	membrane	short membrane	long membrane
leaves	emerging leaf rolled narrow shiny	emerging leaf folded <2mm leaf not shiny apex pointed	sheath rolled >2mm	sheath rolled >2mm	sheath tubular purple stripe on sheath hairy leaf margin

Images courtesy of Michael Moerkerk, Department of Natural Resources and Environment, Victoria

Table 9.4. An example guide to common broadleaf weed species, based on seedling identification keys developed by Moerkerk (1998).

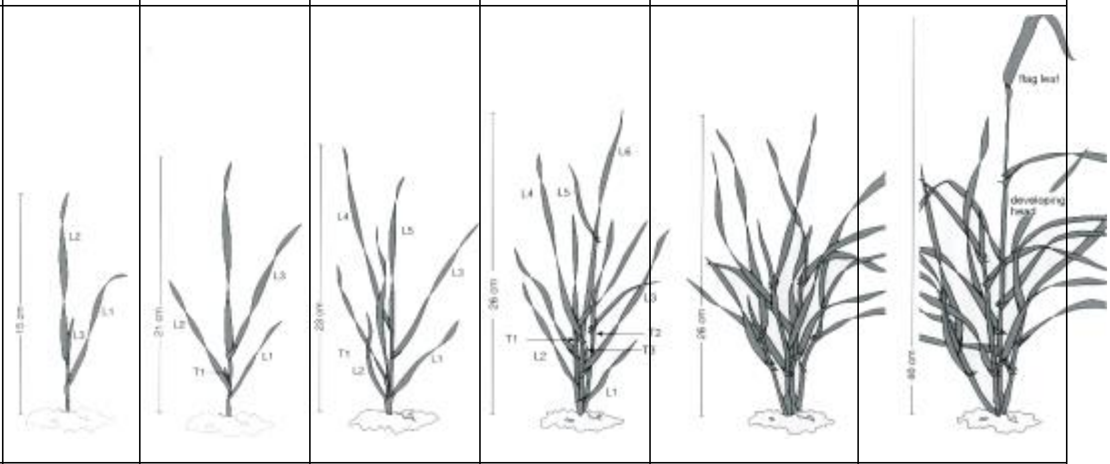
	wild radish *Raphanus raphanistrum*	wild turnip *Brassica tournefortii*	Indian mustard *Brassica juncea*	Paterson's curse *Echium plantagineum*	capeweed *Arctotheca calendula*
					
cotyledon	heart shaped base smooth hairless	heart shaped base smooth hairless	heart shaped base smooth hairless	oval, >3mm apex round hairy	club shaped apex round hairless
1st leaf	Oval hairy margin toothed and lobed prominent veins	Oval hairy margin lobed warty appearance	Oval hairy margin toothed and lobed hairs on petiole	oval long hairs apex pointed	spear shaped white hairs margin lobed first leaves paired

Images courtesy of Michael Moerkerk, Department of Natural Resources and Environment, Victoria

- *Growing conditions* – For herbicides to work effectively, they have to be intercepted by the weed, absorbed and translocated to the site of action within the plant. Plants are likely to be most receptive if not exposed to environmental stresses before, during or after spraying and are actively metabolising. Consequently, high temperatures and evaporative conditions, low temperatures including frost, low moisture conditions and poor soil fertility are important factors in decreasing a plant's susceptibility to herbicide application. Research by Minkey and Moore (1998) over a range of conditions and seasons in Western Australia showed that the ED90 (i.e. rates required for 90% kill) ranged from 75 to 2500 mL/ha for glyphosate, 184 to 3184 mL/ha for paraquat + diquat and 323 to 2500 mL/ha for diclofop methyl. Many farmers attempt to reduce costs by using low rates of herbicides. Under good conditions the outcome may be satisfactory but the risks of failure increase where one or more of the environmental factors are suboptimal for growth. Label rates therefore give the best guide to achieving a proper outcome and therefore should be followed. Using rates higher than that prescribed on the label is illegal Australia.

- *Stage of growth* – Often, herbicide application is a compromise between suitable conditions for herbicide effect, the growth stage of the crop and suitable growth stage of the weed. Labels usually specify the appropriate growth stages, described by leaf number or the Zadok's decimal code (Figure 9.1). As the weeds and crops grow it becomes necessary to change herbicides. As a general rule, the older and larger the weed plant is, the more difficult it is to control by herbicide.

Figure 9.1 Example of Zadok's decimal code for describing the growth stage of monocotyledons (adapted from Mullen *et al.,* 2000)

Zadok's Code	Z12		Z14 – Z21	Z15 – Z21	Z16 – Z23	Z31
						
Growth stage	2 leaf stage – third leaf just emerging		start of tillering – first tiller just emerging	tillering – tillers emerge from base of leaves	fully tillered – tillering finishes when first joint appears on main tiller	Start of jointing – joints or swellings form at base of main tiller

- *Herbicide choice* – Once the target weeds have been identified, the correct herbicide must be chosen to give effective control of those species. Just as importantly, good herbicide rotations must be implemented over time to minimise the chance of resistance developing to one or more groups of herbicides (Table 9.5).

Herbicide Resistance

A characteristic of populations of organisms is genetic variability and a capability to respond to survival challenges. Within plant populations, therefore, will be the capacity to survive herbicide applications through the presence of one or more herbicide resistant genes. The application of a herbicide will remove the susceptible plants in the population allowing those with resistance to survive and set seed. The next generation of seedlings will therefore contain a mixture of susceptible and resistant seedlings and it is possible to have a commercially resistant weed seedling population after three or four applications (years) of the same or related herbicide.

The rate of herbicide resistance development will also be dependent upon the efficacy of the herbicide (i.e. the higher the weed kill the greater the selection pressure towards resistant plants) and the rapidity of generation turnover in the seed bank. Grasses have quick turnover (one to three years) whilst most broadleaf weeds have a proportion of hard seed which slows the turnover.

Extent of Herbicide Resistance

Weed resistance has been a factor since the introduction of herbicides. Its development worldwide was slow in the early years but has been exponential in recent times (Figure 9.2). The Australian experience is following the same pattern some years later and it remains to be seen whether the rapid increase phase will occur given our current knowledge base for its management. Whereas much of the world growth has been to the triazine group of chemicals, Australia's experience has

Table 9.5 Classification of major herbicides according to mode of action (adapted from Mullen and Dellow 1998, Schmidt 1997, Retzinger and Mallory-Smith 1997)

Herbicide Group						
NRA (Aust)	**HRAC (UK)**	**WSSA (USA)**	**Mode of Action**	***Chemical group***	**Active ingredient**	**Example trade name**
A	A	1	Inhibitors of acetyl coA carboxylase (ACC'ase inhibitors)	*Aryloxyphenoxy-propionates (fops)*	diclofop-methyl	Eg, Hoegrass
					haloxyfop	Verdict
					propaquizafop	Correct
				Cyclohexanediones (dims)	Clethodim	Select
					Sethoxydim	Sertin
					Tralkoxydim	Grasp
B	B	2	Inhibitors of acetolactate synthase (ALS inhibitors)	*Sulfonylureas*	Chlorsulfuron	Glean
					Triasulfuron	Logran
				Imidazolinones	Imazethapyr	Spinnaker
					Flumetsulam	Broadstrike
				Sulfonamides	Metosulam	Eclipse
C	C1	5	Inhibitors of photosynthesis at photosystem II	*Triazines*	Atrazine	Various
					Simazine	Eg, Gesatop
					Terbutryn	Eg, Igran
				Triazinones	Hexazinone	Velpar
				Uracils	Bromacil	Hyvar X
	C2	7		*Ureas*	Diuron	Various
					Methazole	Probe
					Tebuthiuron	Graslan
				Amides	Propanil	Ronacil
	C3	6		*Nitriles*	Bromoxynil	Various
				Phenyl-pyridazines	Pyridate	Tough
				Benzothiadiazoles	Bentazone	Basagran
D	K1	3	Inhibitors of tubulin formation	*Dinitroanilines*	Oryzalin	Surflan
					Pendimethalin	Stomp
					Trifluralin	Eg, Treflan
				Benzoic acid	Chlorthal	Eg, Dacthal
E	N	8	Inhibitors of mitosis	*Thiocarbamates*	EPTC	Eptam
					Tri-allate	Avadex BW
				Organophosphorus	Bensulide	various
	K2	23		*Carbamates*	Propham	Clopham
F	F1	12	Bleachers	*Nicotinanilides*	Diflufenican	Brodal
				Pyridazinones	Chloridazon	Pyramin
	F2	28		*Pyrazoles*	Benzofenap	Taipan
	F3	11		*Triazoles*	Amitrole	Various
		13		*isoxazolidinones*	Clomazone	Magister
G	E	14	Inhibitors of protoporphyrinogen Oxidase (PPO)	*diphenyl ether*	Acifluorfen	Blazer
					Oxyfluorfen	Goal
				oxadiazoles	Oxadiazon	Ronstar
H	N	8	Inhibitors of protein synthesis	*thiocarbamates*	Thiobencarb	Saturn
I	O	4	Disrupters of cell Growth (synthetic auxins)	*Benzoic acids*	Dicamba	Banvel
				Phenoxy-carboxylic acids	2,4-D	Various
					Dichlorprop	Various
					MCPA	Various
				Pyridines	Clopyralid	Lontrel
					Picloram	Tordon
J	N	26	Inhibitors of fat synthesis	*alkanoic acids*	Fluoropropionate	Frenock
					TCA	TCA
K	C		Herbicides with diverse or unknown sites of action	*Phenylcarbamates*	Phenmedipham	
	I	18		*Carbamates*	Asulam	Asulox
	K1			*Amides*	Propyzamide	Kerb
	K3	15			Metolchlor	Dual
	L	20		*Nitriles*	Dichlobenil	
		21		*Benzamides*	Isoxaben	Gallery 750
	M	24		*Dinitrophenols*	Dinoseb	
	P	19		*Phthalamates*	Naptalam	Alanap
	Z	8		*Pyrazolium*	Difenzoquat	Avenge
		17		*Organoarsenic*	MSMA	Eg, Daconite
		25		*Amino-propionate*	Flamprop-methyl	Mataven
L	D	22	Inhibitors of photosynthesis at photosystem I	*bipyridyls*	Diquat	Reglone
					Paraquat	Gramoxone
					Paraquat/diquat	Spray.Seed
M	G	9	Inhibitors of EPSP synthase	*glycines*	Glyphosate	eg, Roundup
					Glyphosate-trimesium	Touchdown

N	H	10	Inhibitors of glutamine synthetase	*Phosphinic acid*	Glufosinate-ammonium	Basta

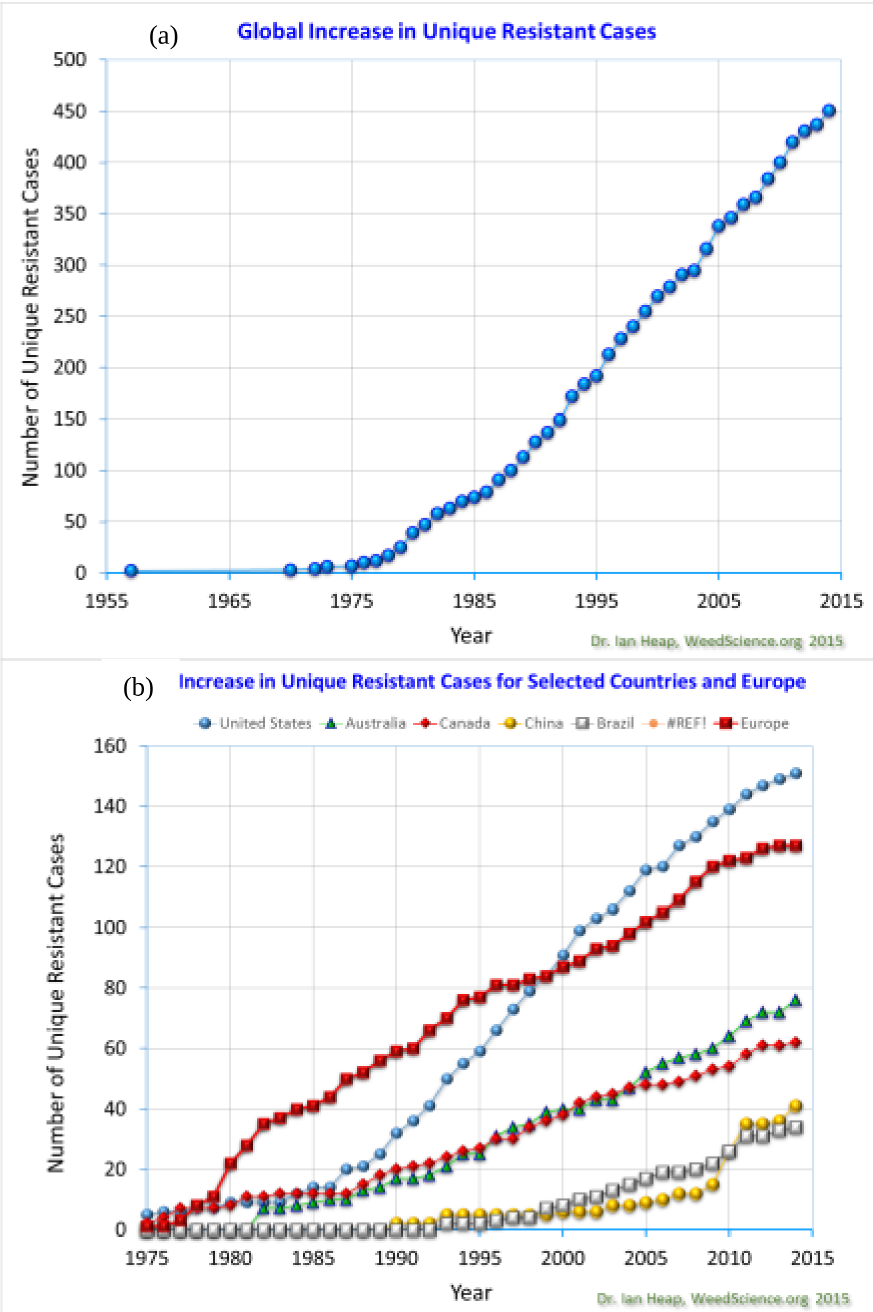


Figure 9.2 Chronological increase of unique herbicide resistance in weeds (a) globally and (b) for selected countries (Heap, 2016)

been mainly to the Group A (‘fops’ and ‘dims’) and Group B (sulfonyl urea) chemicals. The main occurrences have been in annual ryegrass in the winter cropping areas where up to 50% of fields have ryegrass resistance to at least one herbicide group and in rice crops where more than 50% of populations of dirty dora (*Cyperus difformis*) are resistant to bensulfuron. Our farming systems depend on an effective chemical armoury which we must endeavour to maintain effective for the long term.

Whilst the number of unique cases of herbicide resistance may appear low, within any species there may be many resistant populations. Worldwide, the 258 unique cases of resistance occur over 156 species, and more than 210,000 populations have been reported (Heap, 2002). Within Australia, results from the herbicide testing service operated by the Farrer Centre, Charles Sturt University, show that, for annual ryegrass (*L. rigidum*), more than 90% of samples tested are resistant to Group A *fops* herbicides, and over 30% are resistant to Group B herbicides. With large numbers of populations showing commercial levels of resistance, the long term effectiveness of these chemical groups is compromised. Additionally, loss of these herbicide groups places more pressure upon herbicides with other modes of action to control weed populations.

The introduction of herbicide tolerant crop varieties has impacted upon the usage pattern of herbicides, and affect the herbicide group rotations during a cropping rotation. Herbicide groups can potentially be used with more crop types (e.g. triazines with triazine tolerant canola, or sulfonylureas with Clearfield canola), or in novel ways (*e.g*. glyphosate as a post-emergent selective in Roundup Ready crops). Changes in the amount of use, or method of use, may impact on the rate of herbicide resistance development.

Management of Herbicide Resistance

There are four key principles in the management of herbicide resistance. These are:

- non-introduction of resistant weed seed, usually as seed contaminant onto the farm (as previously described);
- rotation of herbicide groups so that a weed population does not have the opportunity to respond only to one herbicide mode of action selection pressure;
- prevention of the seedset of weeds which have escaped from a herbicide application;
- use of non-chemical options for weed control when opportune in association with herbicide control. Such options have been previously described.

Table 9.5 describes the herbicide mode of action group labelling system. The purpose of this scheme is to make it easier for farmers to distinguish between trade names of chemicals (there are many different trade names for the same chemical mode of action) and different modes of action. There is strong correlation between the American and European systems. In comparison, the Australian classification system differs in several respects for the classification of some herbicides. Most notably, inhibitors, such as the thiocarbamates, are split between several Australian groups, rather than being together as in the other systems. The different systems used worldwide makes it difficult to easily compare results from different countries. It should be noted that the order of the groups does not reflect the relative susceptibility of herbicide mode of action to resistance. Ideally, farmers ought not use the same chemical group more than once in a rotation cycle.

Table 9.6 tabulates the first recorded instance of unique herbicide resistance cases within each State. Resistance is generally restricted to only one or two herbicide groups for any particular weeds, apart from annual ryegrass. Due to its genetic variability, resistance has occurred to herbicides in six different mode of action groups. Figure 9.3 presents herbicide resistance data for annual ryegrass tested to five herbicide groups by a commercial testing service. Samples were received either through an industry funded tested scheme, or directly by the service because resistance was suspected. Resistance to the *fops* herbicides is common, and there is also significant resistance to both the *dims* and sulfonylurea herbicides.

It is important to acknowledge that weed survivors are not necessarily resistants. There are many reasons why weeds are present in the crop at the end of the season. Low efficacy of the herbicide applied through poor environmental conditions has been described. Late germinating seeds may miss the herbicide application process altogether, as occurs in wild oats and wild radish with their staggered germination characteristic. It may be due to the individual plants being tolerant of the low chemical rates being applied or resistant to commercially recommended rates. The most satisfactory way of determining the cause is through a herbicide resistance test. For this, seeds of the offending weed plants need to be collected and provided to a herbicide resistance testing service for analysis prior to the next cropping season.

Figure 9.3 Level of herbicide resistance in the four major cropping States for annual ryegrass (*Lolium rigidum*) samples tested for cross-resistance (Broster, unpublished data)

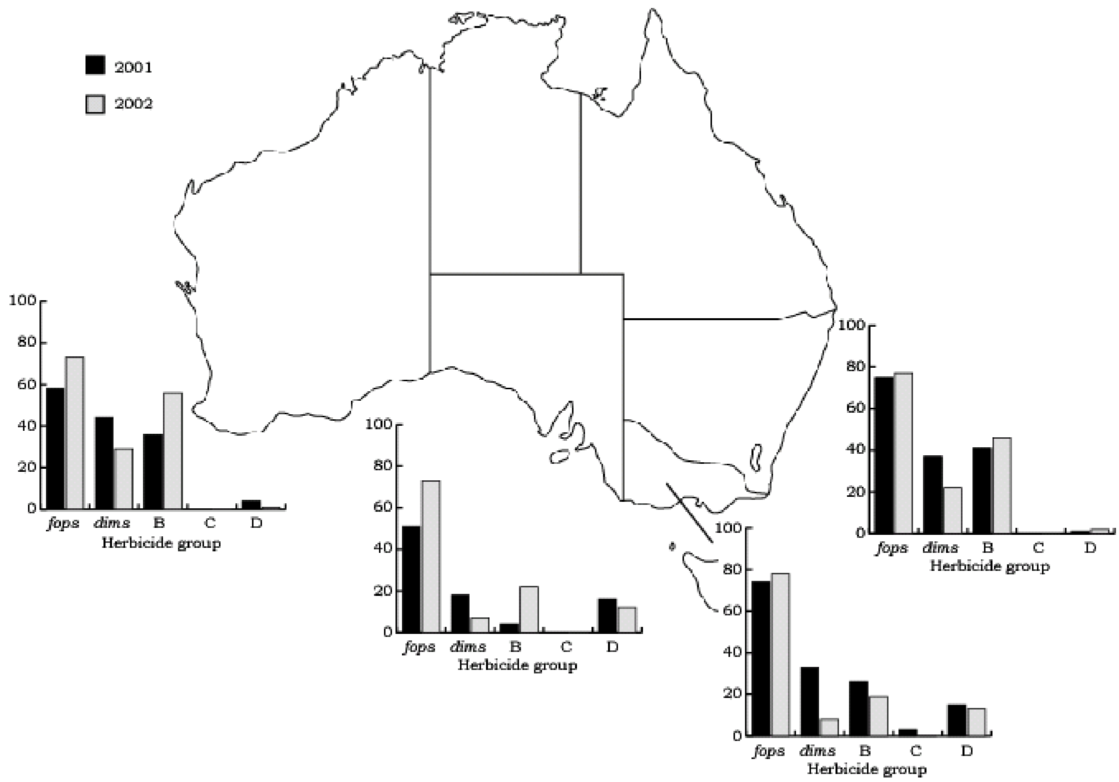


Table 9.6 Herbicide resistant weeds of Australia (adapted from Heap 2002)

Weed species	**Queensland**		**New South Wales**		**Victoria**		**South Australia**		**Western Australia**	
	Year	**Group**	**Year**	**Group**	**Year**	**Group**	**Year**	**Group**	**Year**	**Group**
Arctotheca calendula (capeweed)					1986	L				
Avena fatua (wild oat)			1991	A			1988	A	1985	A
Avena sterilis (wild oat)			1989	A			1989	A		
Brassica tournefortii (wild turnip)									1992	B
Bromus diandrus (great brome)					1999	B				
Cyperus difformis (small flower umbrella sedge)			1994	B						
Damasonium minus (starfruit)			1994	B						
Digitaria sanguinalis (large crab grass)							1993 1993	A B		
Echium plantagineum (Paterson's curse)							1997	B	1997	B
Fallopia convolvulus (climbing buckwheat)	1993	B								
Fumaria densiflora (fumitory)			1999	D						
Hordeum glaucum (wall barley grass)					1982	L	1996 2000	L A		
Hordeum leporinum (barley grass)			2001	A	1988	L	1996	A		
Lactuca serriola (prickly lettuce)							1994	B		
Lolium rigidum (annual ryegrass)			1989 1997	A,B,C,D M	1984 1996	A,B,D M	1982 1996	A,B,C,D,E D	1982 1988	A,B,D C

Phalaris paradoxa (hood canary grass)			1997	A						
Rapistrum rugosum (turnip weed)	1996	B								
Raphinus raphanistrum (wild radish)							1998	B	1997 1999	B C
Sagittaria montevidensis (arrowhead)			1994	B						
Sinapis arvensis (wild mustard)			1996	B						
Sisymbrium orientale (Indian hedge mustard)	1993	B	1994	B			1990	B	1994	B
Sisymbrium thellungii (African turnip weed)	1996	B								
Sonchus oleraceus (sowthistle)	1990	B								
Urochloa panicoides (liverseed grass)	1996	C								

Resistance to Non-Selective Herbicides

Most resistance worldwide is to the selective herbicides. Non-selective, or "knockdown", herbicides are now an integral part of the conservation farming program in Australia and the preservation of their effectiveness is paramount. The two major herbicides are glyphosate (Roundup®) and paraquat/diquat (Spray.Seed®) with glyphosate being used more widely because of its effectiveness on larger weeds and its safety. Isolated resistances to paraquat/diquat have been recorded in barley grass, capeweed and annual ryegrass without further development. The first instances of resistance to glyphosate in 1996 (Pratley *et al*. 1996, 1999 and Powles *et al*. 1998) were cause for concern because of glyphosate's fundamental role in Australian crop production. Since that time, several other instances have been reported. Most of these have been in undisturbed situations such as orchards, vineyards and driveways where repeated use of this chemical has fostered a resistant population. The small number of instances in annual cropping situations need some evaluation in order to manage that scenario. The lessons that emerge are that seedlings survive the knockdown spray, are not destroyed at sowing because of minimal soil disturbance and they are also resistant (or perhaps too advanced) to the selective herbicide used later in-crop. Table 9.7 provides a decision process that involves close monitoring to ensure a satisfactory outcome.

Table 9.7 A suggested decision process for minimising the risk of knockdown herbicide resistance

Year 1

* Prepare seedbed as normal
* Apply knockdown chemical at
  - recommended rates
  - correct growth stages

* Check for knockdown control before sowing

* If satisfactory

Proceed as normal

* If survivors are present:

1. Full soil disturbance before or during sowing
2. If possible control escapes from (1) by post-emergent herbicides
3. Prevent seed set from any escapes from (2)
4. Collect seed of escapes from (3) and test for resistance to all herbicides
5. Harvest paddock **last** to prevent transfer of seed to other paddocks
6. Do **not** sell or keep the seed for sowing to minimise spread

Year 2 onwards

Year 2 onwards	* Use high rates every 3 or 4 years **AND/OR** * Use alternative knockdown herbicide every 3 to 4 years **AND/OR** * Cultivate seedbed and use trifluralin every 3 or 4 years	* Use alternate knockdown herbicide **AND/OR** * Cultivate seedbed and use trifluralin **AND/OR** * Use a tickle early in the season to encourage germination followed by a further cultivation

* In all cases, only use known effective selectives

Herbicide Resistant Crops

Any crop not commercially affected by a selective herbicide is a herbicide resistant crop. However, in recent times there have been the introductions of new varieties which create new patterns of use for old chemicals. Whilst this creates opportunities for farmers, it also creates a new set of risks and this needs to be managed. Two examples are provided.

Farmers have been restricted in growing canola because of weed radish infestation. The availability of triazine-tolerant (TT) canola varieties has overcome this restriction and canola is now more widespread than before. At the same time farmers have tightened their rotations to alternating wheat/canola. This increases the use of triazines in the rotation and the risk of herbicide resistance to that chemical.

The availability of glyphosate resistant varieties (e.g. Roundup Ready cotton and canola) transforms a non-selective pre-planting herbicide to a post-emergent selective (i.e. selective to weeds but not the crop). The option of glyphosate survivor removal at sowing or by a selective in-crop herbicide is therefore no longer as applicable, increasing the risks of resistance to glyphosate. With the knowledge that such resistance can occur, management of glyphosate then becomes similar to other post-emergent chemicals. There will still be a tendency for farmers to use glyphosate as a knockdown pre-planting and as a post-emergent selective. Therefore, vigilance will be needed to manage the resistance threat.

CONCLUSIONS

Weed management is largely common sense and attention to detail. Good agronomic practices will minimise the introduction and spread of weed problems. Wise use of chemicals will preserve the life of useful chemicals and maintain an economic response to future uses of the same chemical. Constant monitoring will reveal problems early when they are easier to address.

There is no single means of achieving weed control. A range of options, both chemical and non-chemical, should be employed in order to minimise the risks of herbicide resistance.

PRINCIPLES

- Preventing introduction and spread will have long term benefits in reduced weed infestation.
- Weeds are not uniformly distributed but occur in patches similarly distributed from year to year.
- The soil contains the seedbank generated over previous years. Depleting the seedbank and preventing recruitment will reduce weed infestations.
- A pasture phase provides a broader range of options for control of weed populations in the cropping phase.
- Different weed species react differently to particular treatments. Management needs to adapt to the particular characteristics of individual species.
- Chemicals only work as well as the species, their growth stage and environmental conditions allow.
- Continual reliance on a single mode of action will encourage the weed population towards a resistant state.

- Integrated weed management, using chemical and non-chemical methods, offers the best chance of long term control of weed populations.

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