Pesticides in Agriculture: Friends or Foe?

Jim Pratley, Deirdre Lemerle, Lyn Fragar and John Kent

Pesticides continue to be major inputs to agricultural production throughout the world. They remain efficient means by which weeds, insects, fungi and other pests are controlled economically. Their continued use and effectiveness is threatened by the prospect of pest resistance. Although Australia is a low chemical user by world standards, the community is concerned about pesticide residues in foodstuffs and in the environment and the perceived health risks.

In Australia, the vast majority of pests are introductions from overseas. Whilst it is perhaps unrealistic to suggest that those existing in Australia can be eliminated, the chances of reducing pesticide inputs rely on an integrated approach incorporating: the prevention of the introduction of new pests through better quarantine and inspection services; the breeding of new varieties with tolerance or resistance to the pest; the development of biocontrol agents for the pest; the utilisation of natural mechanisms such as competitiveness and allelopathy through a better understanding of the biology and ecology of the pests and their hosts; and the increased efficiency and effectiveness of pesticides through research, extension, education and training programs for chemical users.

The risks posed by agricultural chemicals are diminished by the adherence of all parties to the duty of care, i.e. the manufacturer, the reseller, the chemical user and the government through legislative support.

1 INTRODUCTION

Farm chemicals comprise a range of products which include herbicides, insecticides, fungicides, veterinary products, vaccines and feed supplements. In this context, fertilisers are not included. Since the 1970s the expenditure on farm chemicals has increased as a proportion of total cash costs on farms (Fig. 1). This varies according to the enterprise(s) being undertaken (Milham and Davenport 1994). There are few substitutes for chemicals in agricultural production and in most industries maintenance of economically sustainable levels of production will require their continued use as part of an integrated pest management (IPM) strategy. Relative to other costs of production, the direct costs to farmers of chemicals are small and the benefits from their use are often greater than for most other inputs. Such benefits include greater crop and pasture yields through control of pests and diseases, fewer livestock losses through disease and parasite control, better quality produce and lower production costs.

Milham and Davenport (1994) record that FAO has estimated a 30% reduction in farm output if chemicals were removed from world agriculture. They calculate that chemicals yield a benefit/cost ratio in the range of 3.5–4:1.

More than $30 billion is spent annually on pesticides worldwide (Pimental and Greiner 1997). In 1996, Australia spent over $600 million on pesticides, that is a little more than 2% of the world's usage and a 4-fold increase in less than 2 decades. Australia spends considerably more on herbicides than on insecticides or fungicides, being in the proportion of 7:2:1 in expenditure respectively.

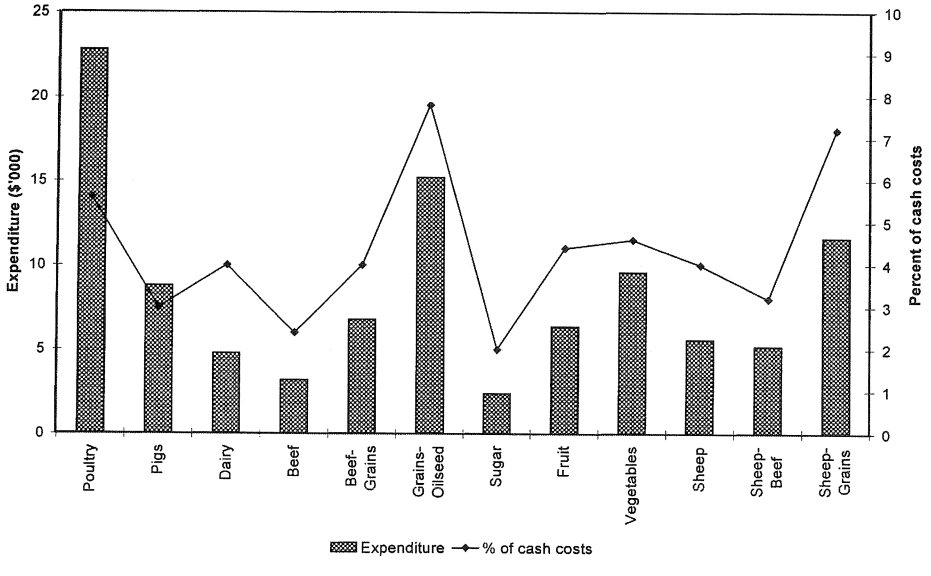

Fig. 1. The on-farm chemical expenditure in Australia and the average cash costs for selected agricultural industries and combinations 1990–91 (Milham and Davenport 1994).

Australia is a dry continent by world standards and thus has lower requirements for insecticides and fungicides in broadacre plant production. Apart from summer broadacre crops most insecticide and fungicide usage is confined to the horticultural industry and to urban use. Particular notable exceptions include heliothis (*Helicoverpa* spp.) infestation in cotton in summer and redlegged earthmite (*Halotydeus destructor*) in germinating winter crops and pastures.

Weeds are the major pests in Australian crop production and are estimated to cost more than $3 billion annually in lost production, contamination of produce, or poisoning of livestock. Further, in the natural environment, weeds are having devastating effects. Some 15% of Australia's flora of 15–20 000 species are alien. About half invade native vegetation and a quarter are already, or likely to become, weeds (Cooperative Research Centre for Weed Management Systems 1995/1996). Groves (1998) reports that between 4 and 6 new additions to the flora of each State per year have occurred over the last 100 years. The rate of naturalisation has increased particularly so in the last 15 years. Whereas most of the early weeds came from Europe, these days the African continent and the Americas are equally as important as Europe as a source of plants naturalised since 1971. The majority of these new incursions have resulted from a combination of inadequate quarantine procedures and policies, having been allowed to enter legally because of some perceived use to humans, as potential crop or pasture plants or for ornamental horticulture (Groves 1998).

Farmers are very dependent on herbicides for profitable crop production. The main weed species sprayed in the winter cropping areas are shown in Fig. 3. Herbicide availability and effectiveness have allowed less reliance on cultivation for weed control. Thus, conservation farming systems that address soil structure decline (Chapter 4), through reducing tillage, have become feasible although they do increase farmer dependence on chemical weed control.

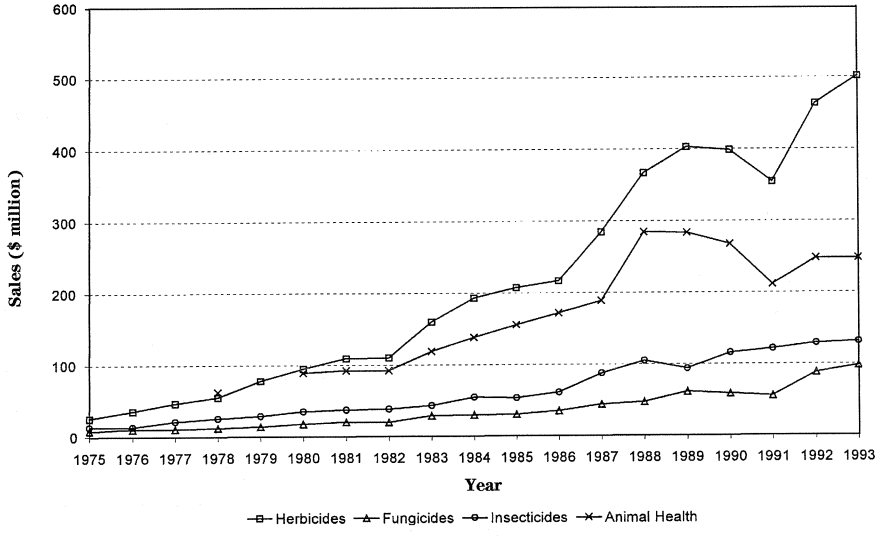

Fig. 2. The expenditure on herbicides, fungicides, insecticides and animal health products in Australia for the period 1975–1993 (ABARE 1994).

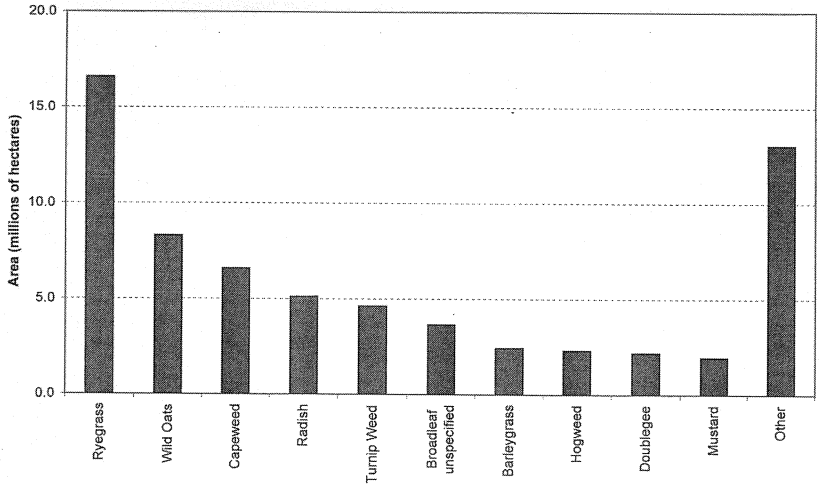

Fig. 3. The area treated for the weeds spectrum in winter crops in Australia, 1997 (CRC for Weed Management Systems, unpubl.).

The publication of 'Silent Spring' by Rachel Carson (1962) focused the attention of the community on the environmental and human health consequences of some of the pesticides in use at the time. Subsequently, various organisations and individuals have conducted campaigns against pesticide use *per se*. Conflict is generated between productivity/product quality and limiting synthetic chemical inputs. In heightening awareness of these issues, Carson has imbued a generation which is more responsible in its attitude to the environment and its management, particularly with respect to pesticide use. This has helped motivate governments to invest in safer chemical use through research and development and education.

Although caution is a commendable attitude to have with respect to pesticide use, it is also necessary to recognise the role of pesticides in the conservation process. Avery (1998) indicates that throughout world history, soil erosion has been by far the biggest problem in agriculture. The availability of broad spectrum herbicides such as glyphosate (Roundup) and paraquat/diquat (Spray.Seed) has enabled farmers to grow crops without, or with substantially reduced, cultivation thereby reducing the risks of soil erosion and its impacts on waterways. More recently, the role of biotechnology in developing pest resistance in crops and hence in reducing pesticide use (e.g. the development of Bt cotton) provides significant prospects for the environment. The control of liverfluke and other internal parasites has rendered meat products much safer for human consumption.

In this chapter, we discuss these issues and evaluate both the benefits and problems associated with pesticide use in agricultural systems. The following main issues are addressed:

(1) The effectiveness of chemicals and their overuse has resulted in the evolution of resistant populations of particular pests to specific pesticides. Is this a threat to the continuation of farming with pesticides as we know it, because useful and low hazard chemicals may be no longer effective in the field? What then are the options for future farming systems?

(2) Pesticides are considered to be risks to the health of society. How large those risks are will depend on the toxicology of the particular pesticide and how it is used;
(3 The community has concerns and there are market implications where pesticide residues are present in commercial product. Residues are also a major environmental issue where the chemical remains active in the soil and in the waterways.

2 PESTICIDE RESISTANCE

Pesticides are an integral part of the farming system in Australia because they are efficient and effective. Some individual chemicals are used at least annually on the basis of their effectiveness, their ease of use and economic attractiveness. Such a policy is a recipe for the evolution of a resistant population of the pest to that chemical and resistance is now a reality in most pest categories. Because chemicals have been used too frequently, resistance will continue to expand unless a wider range of control measures is taken by growers. Some of these issues are now considered in more detail.

Of increasing concern is the existence of pests which are resistant to more than one chemical type. This phenomenon is categorised according to whether the resistance is related to the same or different target sites within the pest for pesticide activity. As a consequence of resistance, pesticides are now generally categorised and labelled according to their mode of action, as indicated in Table 1 for herbicides and Table 7 for insecticides for cotton pest control.

Cross resistance denotes a pest that is resistant to more than one pesticide, but where the pesticides have the same target site. Thus, resistance in weeds to both the aryloxphenoxypropionates and the cyclohexanediones is cross resistance since they both are inhibitors of lipid synthesis through the enzyme acetyl CoA carboxylase (AACase) and are categorised as Group A herbicides.

Multiple resistance refers to a pest which is resistant to two or more pesticides which have different target sites for action and therefore are in different pesticide groups. Thus weed resistance to aryloxyphenoxypropionates (Group A) and to the sulfonylureas (Group B) represents multiple resistance since the former inhibit lipid synthesis (through acetyl CoA carboxylase), whereas the latter inhibit amino acid synthesis through the enzyme acetolactate synthase (ALS).

In some cases, when the herbicide is ineffective, this is due to some degradation prior to its reaching the site of action. In these cases, the resistance is referred to as metabolic resistance.

Herbicide resistance

Given the extensive use of herbicides for crop production, it is thus not suprising that resistance by weeds to particular herbicides, particularly those with good

efficacy and with high use, should emerge. Of concern, however, is the rate of increase of the resistance problem, to the extent whereby herbicides may cease to be a viable management tool for weeds.

Within a weed population it can be expected that there will be a proportion of plants which has the genetic capability to resist the activity of a particular herbicide. The development of a resistant population therefore will be brought about by resistant individuals setting significant quantities of seed at a time when the susceptible individuals in the same population have been removed by herbicides. Over time, therefore, the balance of the population shifts from the original position of mainly susceptible plants to an increasing proportion of resistant individuals.

Extent of herbicide resistance

The first case of herbicide resistance was to triazine herbicides in the early 1960s in the northern hemisphere (Ryan 1970; Gressel 1990; Powles and Howat 1990). By 1986, 38 dicotyledonous and monocotyledonous weed species were documented to be resistant to s-triazine herbicides (Yaacoby *et al.* 1986) and by 1987, herbicide resistance in the northern hemisphere had been documented in 60 weed species (Powles 1987). By 1990, more than 100 species in about 40 countries had developed biotypes which were resistant to herbicides covering 15 modes of action (Holt and LeBaron 1990; Powles and Howat 1990; Powles *et al.* 1991; Jutsum and Shaner 1992). By 1997, 188 species were involved in 42 countries (Heap 1997). An international register has been established by Dr Ian Heap on the internet at http://www.weedscience.com

In Australia, the first report of resistance was in 1980 in South Australia involving annual ryegrass and the herbicide diclofop, Hoegrass (Heap and Knight 1982). By 1991, seven major weed species had been recorded (Powles *et al.* 1991) and by 1997 there were 22 species/herbicide resistance combinations (Table 2) (Heap 1997). Of particular significance is resistance in annual ryegrass which occurs in all the southern mainland States of Australia and it is estimated that more than 4000 farms have the problem. Resistance also occurs off-farm, with 5000 km of railway track in Western Australia having ryegrass resistant to amitrole, atrazine, metribuzin and substituted urea herbicides as a result of more than a decade of broad-spectrum weed control.

More recently, isolated annual ryegrass populations have been shown to have resistance to glyphosate (Roundup) at Echuca in Victoria (Pratley *et al.* 1996) and at Orange in NSW (Powles *et al.* 1998).

The initial development of resistance and rate at which it appears depends on four main factors (Howat 1987; Gressel 1990; Gill *et al.* 1991; Powles and Matthews 1992). These are:

- initial frequency and flow of resistant genes;
- selection pressure (frequency and effectiveness of herbicide applications);
- fitness of resistant biotypes; and
- seedbank dynamics/seed survival.

Table 1. The Australian classification of major herbicides according to mode of action (adapted from Mullen and Dellow 1998)

Group	Mode of action	Chemical group	Chemical name	Trade names
A	Inhibitors or acetyl coA carboxylase	*Aryloxyphenoxy-propionate ('Fops')*	Diclofop-methyl	various, e.g. Hoegrass
			Fenoxaprop-*p*-ethyl	Puma
			Fluazifop P	Fusilade
			Haloxyfop	Verdict
			Propaquizafop	Correct
			Quizalofop-*p*-ethyl	Targa
		Cyclohexanedione ('Dims')	Clethodim	Select
			Clodinafop-propargyl	Topik
			Sethoxydim	Sertin
			Tralkoxydim	Grasp
B	Inhibitors of acetolactate synthase	*Sulfonylurea*	Bensulfuron-methyl	Londax
			Chlorsulfuron	Various, e.g. Glean
			Metsulfuron-methyl	Various, e.g. Ally
			Sulfometuron-methyl	Oust
			Thifensulfuron-methyl	Harmony
			Triasulfuron	Logran
		Imidazolinone	Imazapyr	Arsenal
			Imazethapyr	Spinnaker
		Sulfonamide	Flumetsulam	Broadstrike
			Metosulam	Eclipse
C	Inhibitors of photo-synthesis at photosystem II	*Triazine*	Ametryn	Various
			Atrazine	Various
			Cyanazine	Bladex
			Prometryn	Various, e.g. Gesagard
			Propazine	Various, e.g. Gesamil
			Simazine	various, e.g. Gesatop
			Terbutryn	various, e.g. Igran
		Triazinone	Hexazinone	Velpar
			Metribuzin	Various
		Urea	Diuron	Various
			Ethidimuron	Ustilan
			Fluometuron	Various, e.g. Cotoran
			Linuron	Various, e.g. Afalon
			Methabenzthiazuron	Tribunil
			Methazole	Probe
			Metoxuron	Carrotex
			Siduron	Tupersan
			Tebuthiuron	Graslan
		Nitrile	Bromoxynil	Various
			Loxynil	Various, e.g. Totril
		Benzothiadiazole	Bentazone	Basagran
		Acetamide	Propanil	Ronacil
		Pyridazinone	Chloridazon	Pyramin
		Phenyl-pyridazine	Pyridate	Tough
		Uracil	Bromacil	Hyvar X
			Terbacil	Sinbar
D	Inhibitors of tubulin formation	*Dinitroaniline*	Benfluralin	Balan
			Oryzalin	Surflan
			Pendimethalin	Stomp
			Trifluralin	Various, e.g. Treflan
		Benzoic acid	Chlorthal	Various, e.g. Dacthal

Table 1. (continued)

Group	Mode of action	Chemical group	Chemical name	Trade names
E	Inhibitors of mitosis	*Thiocarbamate*	EPTC	Eptam
			Molinate	Various, e.g. Ordram
			Tri-allate	Avadex BW
			Vernolate	Vernam
		Carbamate	Chlorpropham	Various
			Propham	Clopham
		Organophosphorus	Bensulide	Various
F	Inhibitors of carotenoid biosynthesis	*Nicotinanilide*	Diflufenican	Brodal
		Triazole	Amitrole	Various
		Pyridazinon	Norflurone	Solicam
G	Inhibitors of protoporphyrinogen oxidase	*Diphenyl ether*	Acifluorfen	Blazer
			Oxyfluorfen	Goal
		Oxadiazole	Oxadiazon	Ronstar
H	Inhibitors of protein synthesis	*Thiocarbamate*	Thiobencarb	Saturn
I	Disrupters of cell growth	*Phenoxy*	2,4-D	Various
			2,4-DB	Various
			Dichlorprop	Various
			Mecoprop	Various
			MCPA	Various
			MCPB	Tropotox
		Benzoic acid	Dicamba	Banvel
		Pyridine	Clopyralid	Lontrel
			Fluroxypyr	Starane
			Picloram	Tordon
			Triclopyr	Garlon
J	Inhibitors of fat synthesis	*Alkanoic acid*	Dalapon (2,2-DPA)	Various
			Fluoropropionate	Frenock
			TCA	TCA
K	Herbicides with diverse sites of action	*Amide*	Diphenamid	Enide
			Metolachlor	Dual
			Napropamide	Devrinol
			Propachlor	Ramrod
			Propyzamide	Kerb
		Organoarsenic	MSMA	Various, e.g. Daconate
		Carbamate	Asulam	Asulox
			Phenmedipham	Betanal
		Amino propionate	Flamprop-methyl	Mataven
		Nitrile	Dichlobenil	Various
L	Inhibitors of photosynthesis at photosystem I	*Bipyridyl*	Diquat	Reglone
			Paraquat	Various, e.g. Gramoxone
M	Inhibitors of EPSP synthase	*Glycine*	Glyphosate	Various, e.g. Roundup
			Glyphosate-trimesium	Touchdown
N	Inhibitors of glutamine synthetase	*Glycine*	Glufosinate-ammonium	Basta

Table 2. The extent of herbicide resistance in Australian weeds in 1997 (Heap 1997)

Species	Herbicide Groups[A]
Arctotheca calendula (capeweed)	L
Avena fatua, A. sterilis (wild oats)	A
Brassica tournefortii (wild turnip)	A
Cyperus difformis (dirty dora)	B
Damasonium minus (starfruit)	B
Digitaria sanguinalis (large crabgrass)	A
Fallopia convolvulus (climbing buckwheat)	B
Hordeum leporinum, H. glaucum (barley grass)	L
Lactuca serriola (prickly lettuce)	B
Lolium rigidum (annual ryegrass)	A, B, C, D, E, I, M
Sagittaria montevidensis (arrowhead)	B
Sonchus oleraceus (sow thistle)	B
Sysimbrium orientale (Indian hedge mustard)	B
Vulpia bromoides (silvergrass)	L

[A]Herbicide groups are modes of action as represented in Table 1.

Other factors include the number of weeds present, competitive effect of the crop on surviving weeds, breeding system of the weed, biochemical efficiency of resistance mechanisms, duration of selection pressure, and agricultural practices (Powles *et al.* 1991).

Frequency and flow of genes. Howat (1987) indicates that weed populations prior to herbicide use have a resistance level less than 1 in 10^6. Powles *et al.* (1991), however, suggest that the level of resistance in annual ryegrass is 1 in 10^5 or an order of magnitude either way, depending on the expected mutation rate for diploid organisms. Matthews and Powles (1992) quote a frequency of about 2% resistance to diclofop methyl in unsprayed farm populations across southern Australia, whereas on non-farm sites the level was about 0.2%. This level is sufficient to cause a rapid shift towards resistance if sustained selection pressure is applied.

Selection pressure is the management factor that imposes the largest effect on the evolution of resistance (Gressel and Segal 1990). In a field situation, the application of the commercially recommended rates of herbicide should achieve a high percentage kill of susceptible plants, assuming the application technique is effective. Resistant plants will survive this treatment and reproduce. This selection pressure can result in commercial levels of resistance in the field after as few as three herbicide applications, as has been demonstrated by Tardif *et al.* (1996) and Gill (1995) for annual ryegrass to Group A and B herbicides.

Fitness is the ability of a plant to survive and reproduce under competition. The literature is unclear, with respect to herbicide resistance, as to whether the resistant individuals are less fit than the susceptible individuals in the same population.

Gressel and Segal (1990) consider it likely that resistant individuals should be less fit due to their rapid evolution. Howat (1987) reported that resistant annual ryegrass plants had a relative fitness of 0.64–0.67 in mixed stands and 0.81 in pure stands. Powles (1987) reported that capeweed (*Arctotheca calendula*) and barley grasses (*Hordeum* spp.) were also reduced in fitness as resistants.

The difference in fitness relates only to situations where herbicide is not used. A reduced level of fitness in the resistant population would mean that, when herbicide use ceases, the natural susceptible biotype should increase in proportion to dominate the population.

Seedbank dynamics. The longer the life of weed seeds in the soil, the greater is the buffering effect of susceptible seed from previous years. The shorter the life in the seedbank, the faster the evolution (Gressel 1990; Gill *et al.* 1991). Whereas dormant susceptible seeds provide a dilution effect in resistance buildup, dormant resistant seed in the soil will conversely make control and reduction of resistant seed supplies in the seedbank much more difficult.

Selection pressure is greatest in species which have a uniform germination and low level of seed dormancy. In annual ryegrass, for example, dormancy is considered to be up to 2 years. McGowan (1970) found that 80% of the seed had germinated by the end of May leaving only a small proportion to carry over and dilute the enriched resistant population.

Integrated weed management strategies

Farming systems have become oversimplified and methods other than chemical control have largely been ignored in the last 20 years with the availability of selective herbicides.

For intensive crop production, rotation of herbicide groups is required to reduce selection for resistance. The combination of herbicide rotation with strategic tillage provides some diversity whilst burning or grazing of stubbles can also be effective. In extreme cases, it may be necessary to move out of crop production. The collection of seed at harvest time is reported to reduce substantially the carryover burden (Matthews and Powles 1992). Forage crops grown as break crops in the cropping phase are also being evaluated for weed control.

In ley farming situations, increased options are available utilising the pasture phase. As well as herbicide rotation and strategic tillage, farmers can employ techniques such as winter cleaning, spraytopping, heavy grazing and fodder conservation to reduce accessions to the seedbank. Other management practices which need to be employed include:

(i) minimising the risk of introduction of herbicide resistance through seed contamination and machinery contamination;

(ii) preventing as far as possible the production of seed of resistant plants and minimising its addition to the seedbank, including seed collection at harvest;
(iii) reducing the selection pressure by limiting repeated applications of particular chemical groups;
(iv) increasing competition from crops through increasing sowing rates and choosing more competitive crop varieties (Lemerle *et al.* 1996);
(v) using rotations of crops and pastures which disadvantage the weed through allelopathy and other processes; and
(vi) biological control, especially in pastures and natural vegetation.

Herbicide resistance testing. Farmers are encouraged to have seed tested for resistance to identify those groups of herbicides which will be ineffective and hence should not be used. This process is cost-effective for farmers and important environmentally in reducing the amount of ineffective chemical introduced into the environment. The major deficiency in herbicide testing is the substantial delay between the observation of poor control (mid-winter) and the testing operation (the following autumn), a period of about 9 months. Alternative techniques include a Petri dish bioassay that is rapid and simple (Beckie *et al.* 1990) but perhaps may not reflect field conditions.

Herbicide resistant crops

After two decades of continued release of new selective herbicides, the likelihood of new chemistries becoming available is limited. The costs of their development and the very stringent guidelines that need to be met for any new chemical to be released commercially, together with the limited patent protection offered to the developer, severely inhibit the investment in this direction. Consequently, most herbicides released are variations on existing chemistry and there are no miracle cures for the buildup of resistant weeds that occurs in practice.

Companies are finding new uses for existing commercial chemicals through the development of herbicide resistant crops and pastures. There is now a proliferation of 'Roundup Ready' crops (Fig. 4), triazine-tolerant crops and those with tolerance to the imidizolinones, to glufosinate ('Basta' or 'Liberty resistance) and bromoxynil to name some with particular relevance to Australia. Availability of such crops creates opportunities and produces risks that need to be assessed and managed.

The availability of commercial varieties of triazine-tolerant canolas in Australia in 1997 provides a case study of the role of such crops in the farming system. Canola is a profitable crop to grow and is an integral part of the crop rotations particularly in south-eastern Australia. Widespread canola production had been restricted in the past by the occurrence of cruciferous weeds, particularly wild radish (*Raphanus raphanistrum*). The availability of triazine-tolerant cultivars, although lower yielding than their triazine-susceptible counterparts, provides the opportunity to expand the area sown to canola because of the new capability to control wild radish in-crop.

The widespread adoption of these varieties, particularly in Western Australia in 1997, clearly indicates the demand by farmers for such developments. At the same time there are valid concerns about the likely consequences of such rapid and widespread change to the cropping system. The first is the potential for disease, particularly where rotation principles are ignored by growers and where one particular variety type dominates the market. History reminds us of the risk of being dependent on a restricted genetic base. For example, the maydis leaf blight (*Drechslera maydis*) decimated the US corn crop in the early 1970s where the industry was based on the Texas cytoplasm. In Australia, the introduction of the spotted alfalfa aphid (*Therioaphis trifolii*) put at risk the lucerne (*Medicago sativa*) industry which was entirely based on the variety Hunter River.

The second concern is that this canola provides an additional opportunity to use triazine herbicides in the rotation. Already, simazine is used for weed control in lupin crops and for winter cleaning of pastures. World-wide triazine resistance is the most widespread and there is no reason to believe that regular use of triazines in canola will not lead to resistance. Of major concern is the potential for simazine resistance in silvergrass (*Vulpia* spp.), one of the important grass weeds of temperate winter crops and pastures. Simazine remains about the only effective chemical option for its control, and resistance in that species would create special difficulties. Resistance to simazine has already been recorded in annual ryegrass in Australia (Pratley *et al.* 1993). The extensive use of atrazine in these areas also raises concerns about the prospects of residual carryover into succeeding crops and pastures and the potential impact on groundwater contamination.

Fig. 4. 'Roundup Ready' canola treated with glyphosate (left) and glufosinate (right).

The availability of 'Roundup Ready' crops also provides an opportunity for farmers to simplify their management system by reducing their herbicide spectrum, using glyphosate as both a non-selective pre-planting and a selective (with respect to the crop) post-emergence. From an environmental viewpoint, this is a positive step since glyphosate is a very low hazard chemical with respect to the environment and to personal safety and there is little residual impact from its use. Whereas glyphosate is considered a low risk herbicide for resistance development (Vaughn and Duke 1991; Bradshaw *et al.* 1997), it has been shown to occur in the field (Pratley *et al.* 1996; S. Powles 1998). Adoption of these crops without proper management safeguards can put at risk the life of valuable chemicals. Glyphosate is a fundamental part of the conservation farming system and any risks to its continued use for that purpose must be evaluated and minimised as a priority through appropriate management. The risks associated with these herbicide resistant crops are evaluated in Table 3.

Table 3. Herbicide groups and crop/pasture species most commonly used in the ley-farming system and evaluation of the impact of respective transgenic HR crop cultivars on the environment and farming system and an assessment of risk to that system (Pratley *et al.* 1995)

Chemical group	Impact/risk[A]	Crop/pasture species			
		Wheat[B]	Canola	Lupins[C]	Subterranean clover[D]
Group A	EI	Low	Low	Low	Low
(fops, dims)	FSI	Low	Low	Low	Low
e.g. Hoegrass	R	Low	Low	Low	Low
Group B	EI	High	High	High	High
(sulfonylureas)	FSI	Moderate	High	High	High
e.g. Glean	R	High	High	Moderate	Moderate
Group C	EI	High	High	High	High
(triazines)	FSI	High	Moderate	Moderate	Moderate
e.g. simazine	R	High	High	Moderate	Moderate
Group D	EI	Moderate	Moderate	Moderate	Moderate
(trinitroanilines)	FSI	Low	Low	Low	Low
e.g. Trifluralin	R	Low	Low	Low	Low
Group M	EI	Low	Low	Low	Low
(glycines)	FSI	High	High	High	High
e.g. glyphosate	R	Very high	Very high	Very high	Very high

[A] EI, environmental impact; FSI, farming systems impact; R, overall risk to farming systems if particular herbicide not available.

[B] Wheat represents the winter cereals,

[C] Lupins represents the grain legumes,

[D] Subterranean clover represents the pasture phase.

The triazine-tolerant canolas were developed through conventional plant breeding, however, most of the other herbicide-resistant crops have been achieved through transgenesis, that is the insertion of a resistant gene from another species such as a bacterium. This genetic engineering conjures up in the minds of some, fear of the unknown consequences. There are groups thoughout the world conducting campaigns against the technology. The question must be asked as to whether a technology which transfers a specific gene to do a specific job is of any greater concern than the relatively less controlled process of mutagenesis which has been used for a long time by plant breeders to achieve similar ends.

Such technology offers great prospect for improving the quality of human life. It offers hope to many people suffering genetic disorders. It provides opportunity to reduce or modify pesticide use and to improve productivity to feed the world's population. It is contended by manufacturers and scientists that the risks to society are low and the benefits potentially high but the proviso is that the regulatory framework within which the technology operates needs to provide the safeguards which the community demands. In Australia, those safeguards have been the responsibility of GMAC (Genetic Manipulation Advisory Committee) and its surveillance is described by Millis (1995). In the context of this paper, the implementation in the field of the products of this technology becomes increasingly important. There is an expectation on companies to have much greater stewardship of such products in the field than has generally been the case with previous non-transgenic products.

Parasite resistance in livestock

Infestation of grazing livestock by both internal and external parasites can result in reduced productivity and ultimately death if control procedures are not implemented. Australian livestock producers spent more than $150 million on parasite control in 1996/97, thereby showing their reliance on insecticides. Such reliance has resulted in the development of pesticide resistance, the extent of which is given in Table 4.

Such resistance has a genetic basis, although the inheritance depends on the chemicals being considered. For example, resistance by nematodes to benzimidazole anthelmintics has been shown to be inherited as an incomplete dominant/incomplete recessive trait (Lacey 1985; Dobson *et al.* 1996). The resistance to levamisole is expressed as an autosomal recessive trait resulting in slower development of resistant populations of the parasite. However, the situation with the macrocyclic lactone indectocides (ivomectin and moxidectin) is of greater concern in that the resistance is controlled by gene dominance (Kieran 1994; Dobson *et al.* 1996) and resistance would build up more quickly.

Cattle tick resistance to DDT has been shown as incompletely recessive, to organophosphate as incomplete dominance, and to dieldrin as complete dominance (Brown 1967; Stone 1968).

Table 4. The existence of parasite resistance to pesticides in Australian livestock

Parasite	Chemical
Sheep:	
Nematodes	Benzimidazole Levamisole Ivomectin Moxidectin
Trematodes	Triclabendazole
Body Lice	Synthetic Pyrethroids
Blowfly	Organochlorines Organophosphates Synthetic Pyrethroids
Cattle:	
Cattle Tick	Arsenic Organochlorines Organophosphates Synthetic Pyrethroids
Buffalo Fly	Organochlorines Organophosphates Synthetic Pyrethroids

Mechanisms of resistance

The pesticides for livestock parasites operate in four main ways according to their site of action, as summarised in Table 5.

There are three main mechanisms of resistance development:

- alteration of the pesticide properties in the site of action: this is the most common;
- alteration of the rate of metabolism: this is common amongst the ectoparasites where there is a process of detoxification due to a much faster degradation of the insecticide (Nolan 1986); and
- alteration to rate of intake of the insecticide; the parasite, for example the cattle tick, develops a thicker exoskeleton thereby inhibiting the penetration and absorption of the chemical (Brown 1967).

Multiple resistance has been recorded in the cattle tick, *Boophilus microplus* (Nolan 1986), and in the barbers pole worm, *Haemonchus contortus* (Le Jambre 1993). Of particular concern are the limited chemical options remaining for producers in the control of nematodes and blowfly in sheep, and cattle tick and buffalo fly in cattle.

Table 5. The common categories of pesticide activity according to mode of action against livestock parasites (adapted from Behm and Bryant 1985)

(i)	Interference with neurophysiology or neuromuscular coordination
	Death results usually from paralysis
	Sodium channel blockers: arsenic, synthetic pyrethroids
	Gamma aminobutyric acid blockers: synthetic pyrethroids, macrocyclic lactones
	Acetylcholinesterase inhibitors: organophosphates, carbamates, levamisoles
	Acetylcholine blockers: organochlorines
(ii)	Interference with essential energy metabolism
	Inhibition of phosphorylation: salicylanilide
(iii)	Interference with essential biosynthetic pathways
	Inhibition of protein and enzyme synthesis: insect growth regulators juvenile hormone analogues
(iv)	Interference with cellular activities
	Interruption of cell division: benzimidazoles, triclobendazoles, pyrazinoisoquinalines

Integrated pest management (IPM)

The realisation that simple chemical treatment for parasites is unsustainable has led to strategies that have less reliance on chemicals, prolong the life of existing chemicals but which require a higher level of management by the producer. For this to work, there needs to be an understanding of the biology of the parasite and the epidemiology of the infestation process. These are now well understood for internal parasites and have given rise to control programs such as 'Wormkill' and 'Drenchplan' in New South Wales, 'Wormbuster' in Queensland and 'Wormcheck' in Victoria. These programs are based on the principle that drenches are given at strategic times in the annual cycle of larvae on pasture in order to reduce pasture contamination by eggs to prevent a later increase in larvae numbers. The number of drenches is reduced and rotation of chemicals with different modes of action is incorporated. The most susceptible stock, lambs and weaners, are drenched onto 'clean paddocks' which have not been grazed by sheep for six months. An outline of the Wormkill program is given in Table 6.

Important in this IPM approach is the need for livestock to be in good health and with adequate nutrition, since the nutritional status of the animal can substantially influence the natural or acquired immunity to parasites. Undernourished sheep and cattle are more inclined to harbour internal and external parasites and have higher faecal egg outputs.

The fundamental importance of quarantine for livestock newly introduced to the farm is highlighted. Transfer of livestock between farms provides an opportunity to transfer resistant parasites. Such stock, including rams and bulls, should be treated and quarantined until shown to be clean.

Table 6. The program, WORMKILL, for use in northern New South Wales (Gray 1997)

Date	Adult Sheep and Hoggets		Lambs and Weaners		Grazing management
	Seponver	Broad Spectrum	Seponver	Broad Spectrum	
1 August	♦	♦			
1 November	♦	♦	♦	♦	Move ewe and lambs to low-worm pastures
1 February	♦		♦	♦	Move lambs to low-worm pastures
1 April				♦	

Monitoring of resistance status of the parasites is a necessary part of the management. For internal parasites this is achieved by the Faecal Egg Count Reduction Test which provides information to the producers as to what drenches are likely to be effective. A simpler faecal egg count can be used to monitor levels of infestation.

The availability of 'safe paddocks' where reinfestation risks are reduced has been mentioned as part of the 'Wormkill' and 'Drenchplan' programs. Hall (1990) and Gray (1997) describe practices by which this can be achieved:

- alternate grazing of sheep and cattle since cattle parasites do not infest sheep and *vice versa*;
- alternate grazing by young and mature sheep since the latter have greater resistance to worms. In this way dry ewes and wethers can be used to prepare low risk pastures during summer/autumn;
- in the cropping zone placing weaners and other susceptible stock onto stubble paddocks following harvest.

Biological control. The prospects of biological control for livestock parasites are reasonable. Waller and Faedo (1993) and Thamsborg *et al.* (1997) report a soil fungus that eats parasitic nematodes. Field experiments on cattle in Denmark have shown that pasture contamination with third stage larvae can be reduced by 75% when the dung of infected animals contains spores of the fungus *Duddingtonia flagrans*.

The use of induced sterility in the sheep blowfly (*Lucilia cuprina*) to reduce population size is described by Whitten and Maddern (1993). Initially, the use of irradiation or chemosterilisation was used but without permanent effects on the population. More recently, the use of genetically engineered compound chromosomes to provide less fit individuals has been tried with limited success.

The strategy of using parasite resistant hosts is an important component of IPM. It has long been known that particular bloodlines or individuals exhibit resistance to nematodes or blowflies. Willadsen and Williams (1979), Holroyd *et al.* (1988) and Fordyce *et al.* (1996) have indicated that Zebu Cattle (*Bos indicus*) show high levels of resistance to the cattle tick, whereas the shorthorn and jersey breeds of European cattle (*Bos taurus*) show greater tolerance than other breeds. Such options reduce dependence on pesticides.

Other IPM measures for parasite control include the introduction of dung beetles (e.g. *Onthophagus* spp.) to reduce the habitat for flies and other parasites, mulesing and the breeding of less wrinkled sheep to reduce susceptibility to flystrike.

Insect resistance in crop production

In Australia, the issue of resistance was first encountered with insecticides. The most important example relates to the production of cotton where insect pests, particularly bollworm (*Helicoverpa armigera*), have to be controlled for profitable crops. Cotton was tried in the Ord River region of Western Australia in the 1960s and 1970s. The insect pressure resulted in overuse of insecticides such as DDT and the development of resistant insect populations. The inability of farmers at the time to control economically the insect population caused cotton production to be discontinued in that region.

The cotton industry continued to develop in the Namoi Valley and adjacent river valleys in northern NSW and southern Queensland. In the 1972–73 season, the crop in the Namoi Valley, NSW, was severely damaged by bollworm resistant to DDT. Populations resistant to pyrethroids were identified in the 1983–84 season leading to the development of a strategy to restrict the use of pyrethroids to a maximum of two sprays against one bollworm population only in 1997–98. This has forced the use of other insecticides but concern continues regarding the intensive use of insecticides. Current use is about 8 applications per crop.

The situation continues to worsen with high levels of bollworm resistance to endosulfan and pyrethroids. Carbamate resistance is also increasing but these chemicals need to be preserved as they are needed for the non-transgenic refuge cotton crops and late sprays on transgenic crops (Forrester *et al.* 1997). The chemical groups for bollworm control are listed in Table 7.

Table 7. Insecticides for pest control in cotton according to mode of action (Forrester *et al.* 1997)

Chemical Group	Insecticide
A (organochlorines)	Endosulfan (Thiodan, Endosan, Endosulfan)
B (organophosphates)	Sulprofos (Helothion)
	Profenofos (Curacron, Sabre)
	Chlorpyrifos (Predator)
	Parathion (Folido)
	Monocrotophos (Azadrin, Cronafos, Nuvacron)
C (carbamates)	Methomyl (Larmata, Methomex, Nudrin, Klipp, Kipsin)
	Thiodicarb (Larvin)
D (pyrethroids)	Alpha-cypermethrin (Dominex)
	Beta-Cyfluthrin (Bulldock)
	Bifenthrin (Talstar)
	Deltamethrin (Decis Forte)
	Esfenvalerate (Hallmark)
	Fluvalinate (Mavrik)
	Lambdacyhalothrin (Karate)
E (biological)	*Bacillus thuringiensis* (Dipel ES, Cybour, Condor, Crop King Bollgard, Blobit XL, Blobit XLP, Delfin, Delfin WG)
G (synergists)	Piperonyl butoxide (PBO)

Integrated insect management strategies in cotton

The problem of insecticide resistance in cotton is approached through restriction of particular chemicals to certain periods of the year and the destruction of the crop residues to minimise carryover of pests from year to year. The specific guidelines (Forrester *et al.* 1997) are:

- cultivation of cotton and alternative crop residues as soon as possible after harvest but before the end of August to destroy overwintering bollworm pupae;
- use of recommended larval thresholds to minimise pesticide use and reduce resistance selection;
- monitoring first position fruit retention pre-flowering with the aim of 60% retention;
- use of a test kit during the season to monitor the percentage of bollworm in the heliothis population;
- avoidance of broad spectrum sprays such as organophosphates, pyrethroids or larvicidal thiodicarb early in the season as they reduce the numbers of beneficial insects and increase the chances of mite and aphid outbreaks;
- regular monitoring of mite populations after seedling emergence; broad spectrum insecticides should be avoided;
- alternate use of different chemical groups;
- avoidance of respraying of failures with a product of the same chemistry;
- control of weeds which may act as hosts for mites and other pests, particularly during the winter-spring period.

The application of genetic engineering offers prospects for reducing insecticide use. The bacterium *Bacillus thuringiensis* is used as a biological pesticide (Table 7) but has also been the source of what is known as the Bt gene introduced into cotton, where a toxin within the cotton plant (cv. Ingard) is active against the bollworm. This provides the opportunity to reduce insecticide use by more than 50% (Constable *et al.* 1998).

This technology requires growers to adhere to the insect management plan under the terms of the Ingard Grower Agreement and under the conditions of registration of the Agricultural and Veterinary Chemicals Act, 1994. This requires each grower to grow a refuge crop to produce sufficient *B. thuringiensis* susceptible bollworm moths to dominate the mating with any survivors from the Ingard cotton crop, thereby maintaining resistance at low levels. No preparations containing *B. thuringiensis* are allowed on any refuge crop.

A threat to this program of resistance management is the potential loss of endosulfan as a pesticide. Unlike the other organochlorines which have previously been banned, endosulfan does not have long-term persistence in the environment and has been an important component in IPM strategies to combat resistance. It has been the subject of review by the NRA (NRA 1997), particularly because it has been implicated in fish kills in cotton growing areas, and it has appeared as a residue contaminant in beef and there are community concerns about health and environmental effects of pesticides in this area. The outcomes of the review are that endosulfan supply and use are restricted to appropriately accredited personnel and only to those uses critical to IPM or resistance strategies. The introduction of

transgenic cotton has the capacity to reduce the use of endosulfan substantially, although it remains an essential of pest control in this crop.

Resistance to insecticides is also an issue with pests of stored grain (Banyer *et al.* 1994). As early as the 1960s, stored grain insects developed resistance to maldison. Uncleaned harvesting equipment acted as a source of insect contaminated grain as did survival of insects in treated grain as maldison naturally degraded. This problem was addressed through a program of farm hygiene combined with fumigation (Fishpool *et al.* 1975) and that process remains in place, although the chemicals used have changed over time.

Fungicide resistance

In agricultural crops a combination of breeding for resistance and the use of crop rotations has limited the need for fungicides. Breeding programs must continue to develop new forms of resistance in varieties since the resistance often breaks down as the strains of pathogens evolve.

Fungicide resistance is a significant problem in horticulture. Aspects of this issue are reviewed by Staub and Sozzi (1984), O'Brien *et al.* (1989) and Moody (1997). The main problems occur in vineyards and nurseries where resistance occurs in *Botrytis cinerea* to benzimidazoles, dicarboximides and phenylpyrroles (Moody 1997; Luck *et al.* 1995; Steel 1994, 1996; Steel and Nair 1993), in orchards with apple scab (Penrose 1989), and in cucurbit powdery mildew (*Sphaerotheca fuliginea*) where resistance occurs to ergosterol biosynthesis inhibitors, hydroxypyrimidines, organosphosphates and benzimidazoles (O'Brien *et al.* 1988).

As for herbicide and insecticide resistance, management of the problem involves a monitoring program which incorporates tests for resistance to particular fungicides, a strategy to minimise chemical usage and alternation of preventative and curative fungicides (Penrose 1989; Nair and Holley 1991; Moody 1997). O'Brien *et al.* (1988) suggest that, in order to prolong their efficacy, systemic fungicides should not be used continuously but should be reserved for use during the latter part of crop growth when powdery mildew risk is highest. They also recommend alternating or tank mixing with an effective protectant fungicide.

3 HUMAN HEALTH — ASSESSING IMPACT

Human exposure to pesticides in agriculture depends on the method of application including:

- hand sprayer/application;
- hand dressing, jetting, dipping, backlining and drenching of livestock;
- boom spray application mounted either behind or in front of a tractor or other vehicle;
- mister application in orchards;
- insecticide bomb/fumigation in confined spaces such as silos and for soil and rabbit burrows; and
- aerial application.

The properties which determine the nature and degree of pesticide toxicity include: chemical properties; physical properties; interaction with other chemicals; environmental transformation; and specificity of the pesticide. Pesticides are usually grouped according to their purpose and chemical characteristics.

The dose–response relationship is a fundamental principle in toxicology. It is the relationship between the degree of response of a biological system and the amount of a substance received by the system and implies that a change in the dose results in a concurrent change in the response of the organism. In the dose–response relationship the LD^{50} (the lethal dose for 50% of the population) is used to provide a comparison of the relative acute toxicities of pesticides.

Toxicity studies are generally performed on laboratory animals which include mice, rats, rabbits, dogs and occasionally primates, and these are designed to identify potential toxic effects in a range of situations. The studies generally involve feeding or administration of various doses of the chemical to the animals, and then measurement of the pathological effects to indicate the level, if any, of the toxicity. These are necessary data but questions remain about how extrapolatable the outcomes are to humans.

The NOEL (no observable effect level) is the exposure level at which no adverse health effects occur and is often used to establish acceptable contaminant or exposure levels of substance in the environment and in people. These levels are determined by applying a safety factor to account for possible differences between test animals and humans and to provide protection for sensitive human subgroups. This relationship is used to quantify the toxicity of substances and to determine the ADI (acceptable daily intake) and the MRL (maximum residue limit).

Toxicity in humans requires exposure to the chemicals which are absorbed through the skin (the common route associated with work-related toxicity); injected (mainly in association with vaccines for animal health); inhaled (when pesticides are applied as mists, sprays or gases, and especially important in confined spaces); and ingested (through either contamination of hands, food, drinking water and, more commonly, through accidental or intentional swallowing). Exposure to the odours associated with pesticide application may be a significant problem to some hypersensitive people. However, such odours are added to chemicals to heighten awareness that they are dangerous substances.

Table 8 describes the possible health effects of pesticide toxicity, although more evidence is needed to substantiate these relationships.

Table 8. Possible toxic effects of pesticides on humans

ACUTE EFFECTS (rapid onset, relatively rapid recovery)	Skin and respiratory tract irritation, gastrointestinal effects, neurological symptoms, death
CHRONIC AND DELAYED EFFECTS (after a lapse of time or after multiple exposure)	Behavioural changes, peripheral neuropathy cancer, reproductive effects
SUBCLINICAL EFFECTS (no signs or symptoms but revealed by biological tests)	Cholinesterase inhibition due to chronic exposure to organophosphates and carbamates, behaviour and psychomotor effects

The people most at risk of exposure to agricultural pesticides include, in general order of degree of risk:

- mixers, loaders and handlers of concentrated forms of pesticides;
- pesticide applicators;
- in-field markers for directing application (less commonly used);
- workers who enter sprayed crops, e.g. bug checkers, cotton chippers;
- families of workers who handle pesticides, by pesticide residues on surfaces and clothes (Grieshop *et al.* 1994);
- families whose homes are adjacent to paddocks or crops being sprayed, by pesticide residues on outdoor surfaces, and spray drift;
- other bystanders who may be exposed by spray drift; and
- communities which may be exposed by occasional spray drift or drift of vapours.

Under the Australian Agricultural and Veterinary Chemicals Act, 1994, all agricultural chemical products must be registered before they can be supplied, distributed or sold anywhere in Australia. The National Registration Authority (NRA) is responsible for the assessment and registration of all pesticides for use in all states of Australia. It is illegal for any person to sell, use or have in their possession pesticides which are not registered.

The requirements for applicants desiring registration of their products are specified in a series of publications (NRA 1996*a*, *b*) and are summarised in Table 9.

Table 9. A summary of the NRA requirements for chemical registration in Australia

- Chemistry of the compound, including active constituent, and product details
- Toxicology, including:
  - acute toxicology studies, on the active ingredient and the product
  - short-term toxicity studies
  - subchronic toxicity studies
  - long-term toxicity studies — chronic toxicity studies, oncogenicity studies
  - reproduction studies
  - developmental studies
  - genotoxicity studies
  - additional studies — toxicity of metabolites and impurities, other adverse effects, toxicities of mixtures
  - human toxicological data where available
  - no observable effect level
  - acceptable daily intake
  - first aid and safety directions
- Metabolism and toxicokinetics
- Residues
- Occupational health and safety
- Environment effects, including information regarding physicochemical- and bio-degradation, mobility, field dissipation, accumulation/metabolism
- Environmental toxicology
- Efficacy and safety

Impact on health

Acute poisoning

Pimental and Greiner (1997) summarise the incidence of acute human poisonings due to pesticides. They report that there are three million severe poisonings world-wide each year, with 220 000 being fatal. Developed countries use 80% of the pesticides but less than half the pesticide-induced deaths occur in these countries. They suggest (in conjunction with Forget 1991) that this is due to poor safety standards in developing countries, including lack of protective clothing and washing facilities, illiteracy and inadequate knowledge of pesticide hazards. These comments suggest that a strong legislative framework for protection, together with well-educated users, is a key to reduced instances of accidental poisonings.

Chronic poisoning

In respect of chronic illness due to pesticide use the evidence is less clear. An enquiry by the House of Commons Agricultural Committee of the UK (1987) noted that acute effects of a pesticide are of little help in anticipating possible chronic effects. Such effects are likely to be expressed after very long exposure, perhaps decades. Because of this time frame, cause and effect relationships are difficult to identify clearly due to:

- the wide range of possible causative factors;
- the lack of accurate exposure information likely to be available; and
- the background incidence of natural disease because of ageing.

A review by Maroni and Fait (1993) describes the long-term health effects of prolonged pesticide exposure. They note that despite increasing use of agricultural pesticides, the adverse effects on human health have not been exhaustively evaluated and the role of pesticides in disease development remains controversial. From this review it would seem that:

- when compared with the general population, total mortality and non-cancer causes of death were found to be consistently lower among pesticide manufacturers or users. This finding has been mostly attributed to the 'healthy worker' effect;
- there was lower overall cancer incidence among agricultural workers but an inference of higher risk to myelolymphoproliferative disorders (especially multiple myeloma) and prostate cancer;
- several studies suggest suppression of spermatogenesis and increased hormone levels (FSH and LH) with exposure to dibromochloropropane (DBCP).

Maroni and Fait (1993) concluded that 'in spite of a relative abundance of scientific literature on health effects related to pesticide exposure, very few papers present prerequisites which allow firm demonstrations of causal inferences to be made.'. Thus firm conclusions are difficult to draw because of the difficulties of research in this area previously considered.

It may be that molecular epidemiology provides the opportunity to establish better linkage between exposure to a specific compound and health effects.

Biomarkers have the potential for improving validity of occupational epidemiological observations (Landrigan *et al.* 1994).

More recent reports have tended to confirm an association between agricultural activity with 'possible' pesticide exposure to higher risk of lymphoporetic neoplasms (Weisenburger 1994; Blair and Zalun 1995; Kristensen *et al.* 1996; Waterhouse *et al.* 1996). There has also been a growing literature addressing endocrine disruption (USEPA 1997), chemical sensitivity (IARC 1991; Simpson 1996) and neurotoxicity (Landrigan *et al.* 1994) with unclear outcomes. Clearly, more research is needed.

The dilemma — policy *v.* safety

The dilemma in the pesticides arena is how the political process of formulating policy reconciles with the risk and uncertainty surrounding these issues. The issue of DDT (dichlorodiphenyl-trichloroethane) represents the dilemma in the pesticide debate. This chemical was a major tool in the control of malaria. It was a cheap chemical, easy to apply and effective against many pest species. It did, however, affect wildlife and persisted in the environment, particularly as residues in animal fat tissues. At the time it was promoted by some as a possible carcinogen though subsequent epidemiological evidence does not support that thesis.

Sogoff (1988) espouses that rather than ban DDT use on the basis of evaluating established probabilities that DDT would cause harm to human health and the environment, the authorities bowed to pressure based on ignorance and uncertainty, particularly fear. How then do policy makers make policy in the absence of reliable and reproducible information? With new technologies moving so quickly, those responsible for policy are faced with decisions which are subject to the strong influence of perceptions, correct or otherwise, by the public. Whilst the acute toxicities are relatively simple to address, the chronic health issues are always problematic and are difficult to predict in advance and interpret after time.

Rothman (1990) proposed that 'we spend less time trying to detect general patterns of disease clustering and less time developing new methods to conduct these activities. Instead we should focus more on exposure assessment and where indicated, cleanup.' Neutra (1990) also commented that 'where drawn out science usually fails, prompt service can often succeed.'

The cliche of prevention better than cure is pertinent. In this context we need to maximise the efficiency of pesticide usage whilst minimising exposure of people to such pesticides. All parties are responsible to ensure such a goal is achieved. Stewardship of the chemical by the manufacturer and the reseller, safe and efficient handling and application by the user, monitoring of the high risk groups and the environment by authorities, all within an appropriate legislative framework are components of a proactive management system to reduce the risks. There needs to be effective communication between industry, regulators and pesticide users to achieve a suitable balance. Education is a prime component of these processes.

4 PESTICIDE RESIDUES

Communities remain concerned about the residual properties of pesticides in foodstuffs, for environmental health and persistence in soil and waterways.

Pesticide residues in food

If pesticides are used in situations where a residue may result in a foodstuff, an MRL must be established and there are prescribed withholding periods both for access by grazing livestock and at harvest time. These periods predetermine the legal time of use of the product so that the residue level in the foodstuff does not exceed the MRL. Table 10 shows the requirements for herbicides used in winter crops.

Insecticides and fungicides used on fruit and vegetables require a withholding period between application and harvest to ensure the degradation of the chemical before human consumption. The National Market Basket Survey randomly samples foods produced in Australia and evaluates them for pesticide residues. This is under the auspices of the Federal Department of Primary Industries and Energy. There is, however, no systematic evaluation of food for local consumption, but private or government testing of meat for the export market is systematically evaluated under the supervision of the Australian Quarantine and Inspection Service (AQIS).

The registration requirements for any chemical have been described previously and any chemicals used for the above purposes have been through stringent evaluation before approvals for such use are given.

Perhaps of more significance are the inadvertent or indirect residue issues. There have been sporadic occurrences in Australia where shipments of meat, for example, have been rejected at international destinations because of pesticide residue contamination. Examples include DDT, arsenic and, more recently, chlorfluazuron and, where traceable, farms have been quarantined leading to financial hardship for the producer. Quarantine stays in place until the animals are tested to be clear of the contaminant. In many cases such as DDT, these residues are long lasting and may require more than one livestock generation to achieve clearance.

The most recent case was the contamination by the insect growth regulator chlorfluazuron (Helix), of cattle in north-western NSW. This chemical was applied to cotton crops in the region and, subsequent to harvest, the cotton trash was used as a drought fodder for livestock in the region. The residues of the pesticide were identified in the shipments of meat from those animals and farms were subsequently quarantined for an extended period. Substantial litigation activity has since followed (Long 1998) and the judgements have clearly focused on the duty of care and professional responsibility of all links in the chain: the manufacturer, supplier, adviser and producer.

Table 10. Withholding periods for grazing and harvest following application of selected herbicides used in winter crops (Mullen and Dellow 1997)

Herbicide trade name	Withholding period (days) Grazing[A]	Harvest[B]
Achieve	14	
Agtryne	7	
Amber Post	14	
Banvel M	7	
Bladex	Don't graze	
Broadstrike	Field pea, nil; cereals, 28; chickpeas, don't graze	
Bromoxynil	14	
Correct	Vetch 56	Faba beans 49, safflower 140, chickpeas, field peas, lentils 84, lupins 105, canola, linseed 112
Eclipse	Cereals 14, lupins 28	
Flame	63	–
Fusilade	Canola and lupin 21, fababean 35, fieldpea and chickpea 49	Canola and lupin 119, fababean 35, fieldpea and chickpea 49
Fusion	Canola, linola, linseed, lupins, safflower, vetch 21, fababean 35, chickpea, fieldpea, lentil 49	Fababean 35, chickpea, fieldpea, lentil 49, canola, linola, linseed, lupins, safflower 119
Glean/Siege	Nil	
Gramoxone	1; horses 7	
Harmony M	14	56
Hoegrass	49	
Igran	–	fieldpeas 28
Jaguar	14	
Logran	49	
Lontrel	cereals 28, canola 84	cereals 70, canola 84
Mataven	42	
MCPA	7	
Puma S	Nil; chickpea 98	Wheat, triticale, cereal rye 70
Reglone	1	
Roundup CT	Nil	
Sandoban	7	7
Select	Nil	
Sencor	14	
Sertin		Canola 119, chickpea and fababean 98, fieldpea 70, lentil 140, lupin 35
Simazine	14 (63 for chickpeas and fababean)	Fababean 161
Spinnaker	14	
Spray.Seed	1; horses 7	
Starane	7	

Table 10. (continued)

Herbicide trade name	Withholding period (days) Grazing[A]	Harvest[B]
Targa	Do not graze treated crops	Fieldpea 63, lupin 42, chickpeas and fababeans 84, canola 77
Tigrex	7	
Tillmaster CT	7	
Topik	28	Nil
Tordon 242	7	
Touchdown	1	
Trifolamine	7	
Tristar	49	
Verdict	Medic and clover 7, lucerne 21, vetch 91, chickpea 98, ababean 147, fieldpea 91	Canola, lentils, vetch and lupin 119
Yield	Don't graze prior to crop establishment	
2,4-D ester	7	

[A] Grazing: number of days post-spraying before allowing grazing, to ensure animal produce is free of pesticide residues

[B] Harvest: number of days-post spraying before harvesting grain, to ensure grain is free of pesticide residues.

Other instances of inadvertent residues include the ingestion of forage contaminated by arsenic or the organochlorines. Treated pine logs represent one hazard but perhaps more important are the livestock dip sites used for the control of external parasites. Many farms still have plunge dips and there are more than 1600 cattle tick dip sites which require attention as their function ceases as a result of the cattle tick eradication program. These sites represent long-term contamination from arsenical and organochlorine chemicals and their management to reduce the hazards requires action. This is now happening.

Toxicity to wildlife and other biota

A hidden consequence of pesticide application is the concurrent destruction of the natural predators and parasites associated with the pest. This is reviewed by Pimental and Greiner (1997), who quote the example from Johnson *et al.* (1976) in relation to fungal pathogens. The use of benomyl for plant pathogen control reduced populations of entomopathogenic fungi, resulting in increased survival of the velvet bean caterpillar and cabbage looper (*Trichoplusia ni*), eventually with reduced soybean yield.

In Australia, the most important example is given by Readshaw (1971) where commercial applications of broad spectrum insecticides in pome fruit orchards led to a serious annual problem with orchard mites (*Tetanychus urticae*, the two spotted mite, and *Paronychus ulmi*). This resulted from the insecticides removing the important predator beetle (*Stethorus* sp.), allowing the mites to reach damaging levels each year.

Pimental and Greiner (1997) comment that 'when outbreaks of secondary pests occur because their natural enemies are destroyed by pesticides, additional and sometimes more expensive pesticide treatments have to be made in efforts to sustain crop yields. This raises overall costs and contributes to pesticide-related problems.'.

What this identifies is the need to use pesticides sparingly, based on clear need and in conjunction with other means of pest management, i.e. integrated pest management.

Pesticide residues in waterways and soils

The issue of pesticides in waterways has been addressed by Bowmer (Chapter 3). These pesticides are most likely the result of drift, as happens for example with cotton, components of drainage water from irrigation, as contaminants in soil washed into rivers and streams as the result of erosion or leached into the groundwater. The impact of these will depend on their concentration and toxicity, with insecticides being of greatest concern because of their generally higher toxicity. Dilution in waterways will usually render the pesticides to concentrations that are inactive and transient, but where minimal flows occur the effects can be expected to be more significant.

Pesticide residues in soils under Australian conditions are more likely to be from herbicides. Excessive carryover of herbicide residues from one season to another increases the risk of injury to the following crop or pasture and may contribute to herbicide resistance. The fate of a herbicide after application will be one or more of volatilisation, UV degradation, leaching, runoff through erosion, sorption, plant uptake and chemical and microbial degradation (Ferris and Haigh 1993), and the risks of persistence will vary accordingly, depending on edaphic and climate interactions.

Ferris and Haigh (1993) indicate that if the rate of herbicide degradation follows first order kinetics, that is, the proportion lost is independent of the amount applied, accumulation of herbicides should not occur for herbicides with half-lives of less than one year. They amalgamated data (Fig. 5) from various Australian studies which show that, except for paraquat, herbicide persistence and half-lives were less than one year. Some newer herbicides, however, have extended persistence and guidelines do exist for plant-back periods for crop species affected by such chemicals (Table 10).

The factors affecting persistence of herbicides in soils are described by Ferris and Haigh (1993) and include the following:

(i) Formulation: for example, under Australian conditions granular formulations of triazines have been considered too persistent for agricultural use.

(ii) Dose: the proportion lost over time is independent of the amount applied but the percentage herbicide loss may decrease at high doses.

(iii) Moisture: herbicide persistence tends to be more significant in dry soils than in wet soils as degradation of the herbicide declines in the absence of moisture.

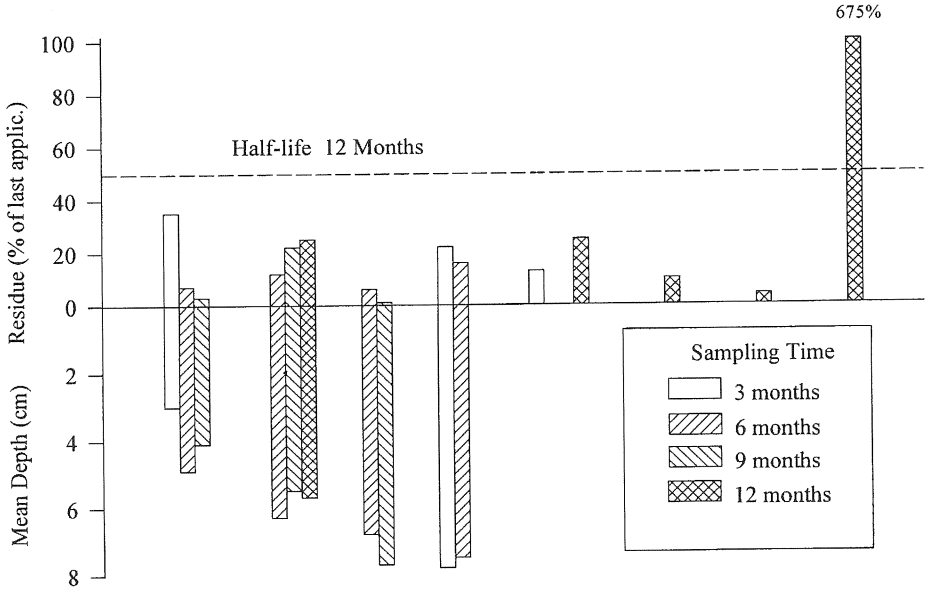

Fig. 5. Persistence and movement of selected herbicides in soil. Degradation rate curve equivalent to a herbicide with a half-life of 12 months. Data from Weiss (1964), Bowmer (1972), Osborne and Donohoe (1977), Johnstone *et al.* (1986), Ferris *et al.* (1989), Fremlin (1989), Holford *et al.* (1989), Paraquat data from 7 years of application (from Ferris and Haigh 1993, reprinted with permission from *Pesticides Interactions in Crop Producation: Beneficial and Deleterious Effects*, ed. Jack Altman. Copyright CRC Press, Boca Raton, Fl.).

(iv) Temperature: degradation of herbicides will be more rapid with increasing temperatures providing adequate moisture is present.

(v) Microbial activity: soil microorganisms may use herbicides as a carbon source and with repeated applications of a particular herbicide it can be expected to build up the population of degrading microbes. This enhanced degradation renders the herbicide relatively ineffective, as previously described (Hole and Powles 1997). Because microbial activity is related to soil organic carbon levels, the maintenance of these levels becomes important in reducing the persistent activity of the added pesticides.

(vi) Soil pH: the pH of a soil will enhance or inhibit the degradation of particular herbicides. The corollary is that pH will influence the persistence of such herbicides (Table 11). Three examples are discussed.

Imazethapyr in acid soils. Imazethapyr (Spinnaker) is a Group B herbicide used for the control of broadleaf weeds in legume crops and pastures. The behaviour of the imidazolinones in soils is reviewed by Mangels (1991) who concludes that the most important factors are pH and organic matter. The herbicide is more tightly bound to soils of low pH making it less available for microbial breakdown and therefore more persistent in those soils. Its use in legumes requires adherence to recommended plant-back periods as identified in Table 11, to avoid damage in

cereals and canola. The low organic matter levels in most Australian soils would reduce the rate of microbial breakdown. With limited moisture available during the summer period in southern Australia, the opportunity for microbial activity is decreased, thereby enhancing the persistence and potential crop damage, especially in low pH soils.

Chlorsulfuron in alkaline soils. Chlorsulfuron is also a herbicide belonging to Group B. It, however, is classified as a sulfonyl urea and persists in alkaline soils to the extent where follow crops can be damaged. Table 11 describes the plant-back periods relating to soil pH under Australian conditions.

Atrazine. Degradation of atrazine is higher at low pH. Crop damage has been confined mainly to double cropping areas of the summer rainfall areas where it is predominantly used. There is the potential for residues to persist into the following winter cereal crop. The availability of the triazine-tolerant varieties of canola has resulted in its more widespread use to the winter rainfall areas across a range of soil types and soil pH. The dry summers reduce the opportunity for breakdown to occur in these areas and increase the risk of crop damage.

Despite the above examples, herbicide persistence in Australian soils has not been a major production impediment. Implementation of best management practices should ensure that the risks are minimised. The issue with respect to the environment is less clear and should be monitored.

Pesticide mobility in soils

The movement of pesticides in soils is potentially a serious issue because of the potential to leach into the groundwater. There has been considerable research on this issue overseas, although little in Australia, and large differences have been reported in the leaching of herbicides in laboratory studies (see Fig. 5 for limited Australian data). However, under field conditions this has rarely been a problem for dryland agriculture in Australia, presumably counteracted by the upward movement of water in the soil through evaporation. However, the incidence of rising watertables increases the risk of groundwater contamination and a monitoring program needs to be implemented to assess the risks.

In circumstances where high rates of leaching occur, such effects are possible. Lighter sandy soils are more vulnerable as they are more readily leachable. Whilst the risks to date have been low, herbicides such as atrazine have been implicated and the increased widespread use of the triazines on canola, particularly on sandy soils, increases the risks.

Evidence from the US suggests that 50% of the groundwater and well water is or has the potential to be contaminated (Pimental and Greiner 1997). The three most common pesticides found were the insecticide aldicarb and the herbicides alachlor and atrazine (Osteen and Szmedra 1989). Concerns are that few microorganisms exist in groundwater to effect degradation (Pye and Kelly 1984) and groundwater recharge rates are very low. Amelioration is therefore a long-term process.

Table 11. Minimum recropping interval after application of selected residual herbicides in crop rotations in NSW (Mullen and Dellow 1998)

CROP	HERBICIDE										
	metsulfuron	chlorsulfuron			thifensulfuron	triasulfuron			imazethapyr	imazameth	flumetsulam
	5.6–8.5*	≤6.5*	6.6–7.5*	7.6–8.5*		≤6.5*	6.6–7.5*	≥7.6*	all soils		
barley	6 w	9 mo	9 mo	18 mo	9 mo	12 mo	12 mo	12 mo	10 mo	4 mo	3 mo
canola	9 mo	12 mo	22 mo	-	9 mo	12 mo	22 mo	24 mo	34 mo	36 mo	9 mo
cereal rye	6 w	3 mo	3 mo	18 mo	3 mo	12 mo	12 mo	12 mo	-	-	-
chickpea	9 mo	-	-	-	9 mo	12 mo	22 mo	24 mo	10 mo	4 mo	3 mo
cotton	-	-	-	-	-	-	-	-	-	34 mo	-
fababean	9 mo	12 mo	22 mo	-	9 mo	12 mo	22 mo	24 mo	-	-	9 mo
field pea	9 mo	12 mo	22 mo	-	9 mo	12 mo	22 mo	24 mo	-	-	3 mo
Japanese millet	14 mo	-	-	-	4 mo	24 mo	24 mo	24 mo	-	36 mo	-
linseed	9 mo	12 mo	22 mo	-	9 mo	12 mo	22 mo	24 mo	-	36 mo	-
lucerne	9 mo	12 mo	22 mo	-	9 mo	12 mo	22 mo	24 mo	10 mo	12 mo	3 mo
lupin	9 mo	12 mo	22 mo	-	9 mo	12 mo	22 mo	24 mo	10 mo	-	9 mo
maize	14 mo	18 mo	26 mo	-	6 mo	24 mo	24 mo	24 mo	-	36 mo	-
medics	9 mo	12 mo	22 mo	-	9 mo	12 mo	22 mo	24 mo	10 mo	36 mo	-
mungbean	-	-	-	-	4 mo	24 mo	24 mo	24 mo	-	12 mo	-
oats	9 mo	6 mo	9 mo	18 mo	9 mo	12 mo	12 mo	12 mo	22 mo	36 mo	3 mo
Panorama millet	14 mo	-	-	-	14 mo	24 mo	24 mo	24 mo	-	36 mo	-
safflower	9 mo	12 mo	22 mo	-	9 mo	24 mo	24 mo	24 mo	22 mo	36 mo	-
sorghum	14 mo	18 mo	26 mo	-	4 mo	24 mo	24 mo	24 mo	-	24 mo	9 mo
soybean	14 mo	18 mo	26 mo	-	4 mo	24 mo	24 mo	24 mo	-	-	-
subclover	9 mo	12 mo	22 mo	-	9 mo	12 mo	22 mo	24 mo	10 mo	-	3 mo
sunflower	14 mo	18 mo	26 mo	-	4 mo	24 mo	24 mo	24 mo	-	24 mo	9 mo
triticale	6 w	-	-	-	3 mo	12 mo	12 mo	12 mo	10 mo	-	-
wheat	10 d	-	-	-	3 mo	-	-	-	10 mo	4 mo	-
White French millet	14 mo	-	-	-	14 mo	24 mo	24 mo	24 mo	-	-	-

* pH (1:5 water)

d = days; w = weeks; mo = months

Other herbicides:

metosulam: Do not plant susceptible crops such as canola or any Brassica crop, field peas, beans, medics, lucerne or sub-clover for 9 months after application.

picloram: Do not plant susceptible broadleaf crops such as soybean, grain legumes, pasture legumes and oilseeds within 12 months of applying herbicide. Cereal crops and grasses are normally unaffected.

chlorpyralid: Residues in straw of treated crops can affect subsequent susceptible crops. Crops such as chickpeas, faba beans, fieldpeas, lentils, lupins, lucerne, medics, safflower, sub-clover and white clover should not be planted for 9 months when up to 0.3 L ha^{-1} has been applied; for 12 months where between 0.3-0.5 L ha^{-1} has been applied. Where 0.5 L ha^{-1} has been used fieldpeas should not be planted for 2 years.

Often overlooked is the potential for pesticide mobility associated with soil particle movement. In Denmark, for example, research is investigating adsorped pesticides being carried down cracks in the soil profile on soil particles, thereby having the potential to link up with groundwater (S. Christensen 1998, pers. comm.).

5 CHANGING CORPORATE STRUCTURE AND PESTICIDE SUPPLY

Commercial plant breeding and seed sales worldwide are no longer the domain of small breeders and regional companies. This is now dominated by multinational agrichemical companies with fewer than the top ten seed companies controlling more than 40% of the global seed market. This concentration is increasing.

In Australia, commercial seed companies have controlled the summer crop seed market for decades, except for the rice industry which is dependent upon and has funded accordingly the NSW Agriculture State Government agency to produce new varieties. In the winter crop production scene, State agencies continue to be major providers of new varieties, funded largely through the Grains R&D Corporation, although some Cooperative Research Centres are also making contributions in selected areas, notably legumes, and with molecular biology. The development of pesticide resistant varieties, however, will be an increasing role for the agribusiness sector.

The top 10 agrichemical corporations accounted for more than $50 billion or more than 80% of all agricultural chemical sales in 1996. Extensive amalgamations have since taken place and most of the major players have taken over biotechnology and seed companies or established strategic alliances to ensure control of pesticide resistant variety production and marketing.

Duke (1995) indicates that sale of seeds is the ultimate way of moving the biotechnology to the market place: in the case of herbicide-resistant crops, this is to increase herbicide sales since the economic driving force for herbicide-resistant crops is herbicide sales, not profit from seed sales. Whilst transgenesis is used to improve agronomic characters, food quality, resistance to insects and plant pathogens, Duke identifies that herbicide resistance is the only trait imparted by genetic engineering thus far to be tied to the sale of another product, i.e. the herbicide.

The concentration of supply of seed and herbicides in a limited number of corporations represents both a threat and an opportunity in terms of environmental concerns. The threats of further rationalisation of the seed and herbicide industries raises concerns associated with monopolistic or oligopolistic systems. From a farmer's viewpoint a reduction in options is a limitation on being able to have a sustainable ecosystem. Provided the options are available and industry rationalisation does not proceed too much further, a healthy level of competition will continue. The smaller number of easily identified corporate players does, however, provide an opportunity to ensure that these corporations

have a strong sense of stewardship of their products and how they are used. These companies must accept that the agricultural industry's reputation as one sensitive to environmental management is now an expectation of the community at large. It is in everyone's interest to ensure that it is done and is seen to be done.

The impact of generics

The farm chemical industry in Australia is dominated by relatively few manufacturers and most are subsidiaries of overseas parent companies. These have the responsibility for the registration processes to enable the compounds to be used, including the R&D effort. These companies usually import the active ingredient to reduce manufacturing costs and to avoid costs of compliance with local manufacturing and site regulations (Milham and Davenport 1994).

Some companies, however, focus on the production of 'off-patent' products which they offer on the market at reduced prices thereby increasing competition. Other generics are imported from countries where the cost of production is much lower and where, in some cases, patent obligations are not recognised.

Farmers are the beneficiaries of the lower price for generic chemicals but the downside of their use is the lack of stewardship by some manufacturers and often lower quality of at least some of the products. The lower price mentality may lock farmers into frequent use of particular products and an enhanced risk of resistance with clear implications for the proprietary product.

Australia is a small market by world standards and primary industries suffer through the lack of availability of some suitable chemicals because of the cost and the stringent regulations required to register a chemical in Australia. The lack of sufficient patent protection in Australia is also an impediment to a suitable return on the R&D investment for companies and the generic manufacturers are not inclined to undertake the R&D and registration requirements themselves.

This therefore represents a real dilemma for the industry. Farmers want a continuing flow of new products on the market to increase their options but also wish prices to be as low as possible. It is difficult to see both being achieved and the question is raised as to whether patent periods should be extended sufficiently to provide for an adequate return on investment in R&D and registration requirements without negating industry competition.

The trends in the corporate chemical world where the control of the crop, the biotechnology and the chemical is vested in the one company is a response to this dilemma and provides the necessary protection to that company's R&D investment.

6 THE NO-PESTICIDES OPTION

Organic farming is promoted as a sustainable alternative to the high-pesticide input agriculture. Hassell and Associates (1995) report that the total Australian market for organic produce has risen from $28 million in 1990 to $80.5 million in 1995, although this rate of growth is not likely to be maintained. Producers

represent less than one percent of farmers and total organic food sales represent only about 0.2% of total food sales in Australia.

Most of the organic produce is sold locally, although the proportion varies between States. There are significant restraints on interstate trade through phytosanitary regulations, including controls on fruit fly and codling moth as well as fumigation of grains shipped to Western Australia.

The Hassell report indicated that surveys had shown a somewhat negative picture for organic farming in that:

- Consumers since1989 have become more confident that government action will prevent contamination of food with chemicals; others feel that too little is being done.
- Athough the amount of organic food purchased has increased, non-purchasers are less likely to buy than previously due to lack of availability, quality and particularly price.
- Consumers want a single organic logo and labelling system to reduce misrepresentation of products and the associated scepticism.

Despite these concerns, organic farming is an alternative which will maintain a small place in the market.

Avery (1998) questions, however, whether the lower yielding alternatives of organic and traditional peasant farming systems should be encouraged. He proposes that the biggest danger to the world's wildlife is not from pesticides or urban expansion but from expansion of low yield farming. World food demand will at least double in the next 50 years through a combination of a 50% population increase to 8.5 billion and diet improvement. The alternatives indicated by Avery are that by 2040 we must be able to triple the yields of the world's existing farmlands, which have relatively low density of wild species, or lose millions of hectares of wildlands and a huge proportion of our wild species through the expansion of low yield agriculture. By necessity, this will require the continued use of pesticides, embracing biotechnology and increased investment in agricultural research. Community and legislative pressures will continue to maintain scrutiny over pesticide use.

7 MANAGING THE RISKS

Pests are an integral part of the production and natural ecosystems. In Australia, most are introduced and therefore do not necessarily have natural predators and their control is dependent to a large extent on the use of pesticides and will be for the foreseeable future. The use of pesticides, however, raises questions about safety to people, wildlife and the environment generally, as has been described. It is paramount, therefore, that the industry and governments accept responsibility so that it can be demonstrated to the community that pesticide use is well managed and that there is sensitivity to the concerns.

Such assurances can be well founded where proper education and training is in place, where the appropriate legislative support is provided and strong research

support is guaranteed. This will enable the search for safer chemicals or safer use of chemicals, the development of new technologies to reduce pesticide inputs and better understanding of the biology and ecology of the pests to be controlled.

Ensuring correct use

Education, training and accreditation will be an ongoing input to agricultural and horticultural production, being a necessary part of any IPM program. Whenever pesticides are used it is encumbent upon the users that all safeguards are in place to ensure maximum effectiveness and minimal risks to the community and to the environment. These can be achieved by application of the following principles:

- by ensuring that there are adequate government safeguards over pesticide manufacture, sale and use;
- by ensuring that all personnel in the manufacturing, distribution, sale and use chain are knowledgeable and skilled, and practise good stewardship;
- through the development and implementation of industry quality assurance programs to ensure the highest possible standards; and
- through the correct selection, adjustment and operation of application equipment.

Much of this is in place in Australia and there have been millions of dollars invested in quality assurance and training programs. Despite this, community concerns remain and education programs are required to inform the community of the true levels of risk and that appropriate safeguards are in place.

Government regulation

Apart from the Common Law 'Duty of Care' responsibility which every person must exhibit, there is a range of legislative requirements at both Federal and State Government levels controlling the way in which pesticides are manufactured, distributed, sold and used. The strictest safety standards apply.

In each State and Territory, legislation is in force to regulate how agricultural and veterinary products are used. In most states it is a requirement to follow label directions unless a permit is obtained from the NRA. Other state legislation regulates such aspects as protection of the environment, protection of people in workplaces (Occupational Health and Safety Acts), storage and transport of pesticides (Dangerous Goods Acts), and the level of residues allowed in foodstuffs (the MRL). MRLs are established such that there is a very wide safety margin for consumers of the foodstuff. However, where the MRL is exceeded this is considered a positive indication of incorrect use of the product. In Australia there have been very few contraventions of MRLs detected since extensive testing procedures have been in force.

The major deficiency in pesticides legislation in Australia remains the inconsistency in regulations between States. Uniformity would enable standard procedures nationally and simplify registration processes.

Industry training programs

To ensure that the legislative requirements are understood and observed, and that all involved in the stewardship of pesticides from manufacture to final use are knowledgeable and competent, a number of industry training and accreditation programs have been developed and implemented by the industries for their members. The most significant of these are the two national programs: the Agsafe Farm Chemical Industry Training and Accreditation Program, and the Farmcare Australia Farm Chemical User Training Program.

The Agsafe Program. In 1987, the industry association representing the vast majority of pesticide manufacturers, distributors and resellers (formerly the Agricultural and Veterinary Chemicals Association, AVCA, now the National Association for Agricultural and Veterinary Chemicals, AVCARE) introduced a comprehensive training and accreditation program for all industry members. The program is under the control of Agsafe Ltd, the independent training and accreditation division of AVCARE.

The program involves accreditation of premises and personnel. Premises accreditation asserts that all pesticide storage premises which require licensing under government legislation must meet the requirements set down under that legislation and be assessed and accredited by Agsafe. All industry personnel handling, storing, selling or giving advice to users of pesticides must also undertake a comprehensive training and assessment program covering the principles of IPM, product label interpretation, legislative requirements, environmental protection, toxicity and safety, the storage and transport of Dangerous Goods, and emergency procedures and planning. Organisations failing to meet the requirements have industry sanctions levied against them. By April 1998, some 12 000 industry personnel had been trained and accredited.

The Farmcare Australia Farm Chemical User Training Program. The Farmcare Australia program, initiated in 1990 by the National Farmers' Federation (NFF) and the Rural Training Council of Australia (RTCA), aims to ensure that all users of agricultural and veterinary chemicals are competent so that the products are used correctly and the environment, community and markets are protected.

The training covers the correct selection and use of pesticides as part of IPM, personal safety, understanding legislation, interpeting product labels and material safety data sheets, environment protection and record keeping as well as the correct application of products, for example, equipment selection, adjustment and calibration.

The Farmcare Program is coordinated nationally by an independent Board, and training delivery is the responsibility of individual state and territory organisations and a network of trained and accredited instructors. Training is based on endorsed national industry competencies and an accredited national curriculum.

The impact of the Farmcare Program has been exceptional with some 85 000 people trained Australia-wide in just 8 years (Fig. 6). The program is used as the basis for more advanced industry-specific training as well as a prerequisite for

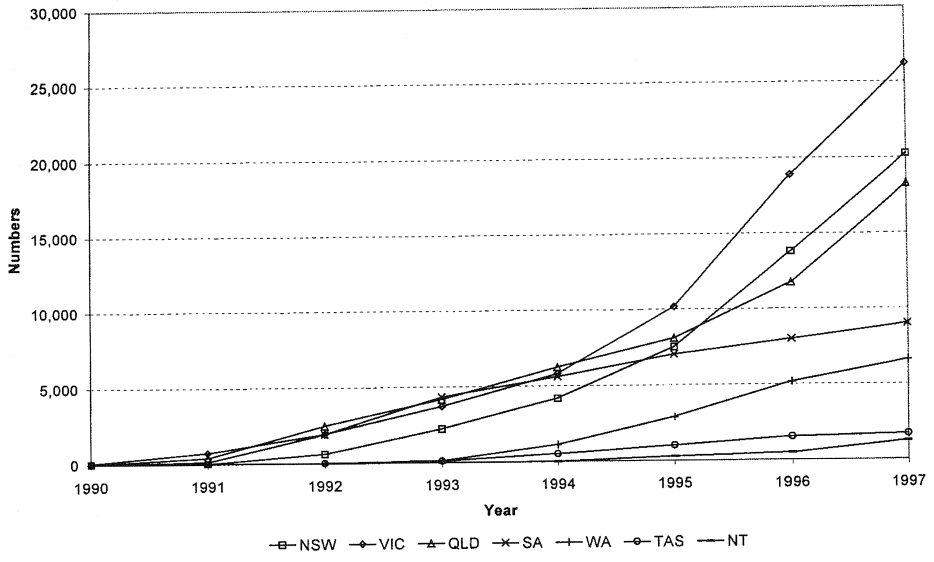

Fig. 6. The number of trained personnel in the Farmcare Australia Farm Chemical User Training Program by State (Kent 1998).

industry quality assurance certification. The training has been introduced into high schools, labour market programs, as well as vocational education and tertiary education courses in agriculture, horticulture, viticulture and environmental studies.

In Victoria, this course is a prerequisite to obtaining a permit for the use of products of greatest hazard to people and the environment (e.g. Schedule 7 products, atrazine). Other States are likely to implement similar requirements. The recent NRA review on endosulfan recommends its use only by licensed users trained under this program.

To date, this accreditation process is industry driven and the question always remains as to whether such programs should be compulsory. The value of a compulsory program is that pesticide application is not done in ignorance and the risks of transgression are minimised.

Industry quality assurance programs

Some agricultural industries or industry sectors have introduced quality assurance (QA) programs to ensure that produce sold meets set standards of quality. The rationale behind this is that if produce meets consistent and predetermined standards, then that will be a marketing advantage and hence be more profitable. Examples of industry QA programs include Cattlecare, Clipcare and Flockcare.

Quality assurance usually involves every aspect of production and marketing, including pesticide use, and in many cases the Farmcare Australia Farm Chemical User Training Program is the basic standard training required. In this way, suppliers can demonstrate that the foodstuffs have been produced by growers

who are competent in chemical use and understand the implications of pesticide residues and how to prevent excess residues. Often the introduction of QA has implications for suppliers of raw materials. For example, many wineries require suppliers of grapes to restrict pesticide use to a specified list of products and to keep records of all pesticide use. Some supermarket chains also require that all fruit and vegetables supplied be grown by producers who are trained and accredited in pesticide use.

Correct application of pesticides

If pesticides are to work as intended, with safeguards for residue levels, the community and the environment, it is essential that pesticides are applied accurately and safely. In many cases, the application of pesticides is the weak link in the stewardship chain. The way pesticides are applied is as important as the selection of the pesticide to use.

Application technology entails the selection of the most appropriate equipment for the pesticide, the intended target and the situation in which the pesticide is to be used, as well as following product label directions. Equipment must be correctly adjusted and calibrated and operated by competent operators to ensure the correct dose is applied where it is needed, at the right time.

Given that technology changes so rapidly, it is necessary for the education and training process to be ongoing.

The role of government

Governments have a fundamental responsibility to provide the community with adequate security through legislation and support services. This has already been discussed in relation to registration of chemicals and of new technologies and for education.

They must also play a role in protecting industries from the introduction of pests and diseases since such prevention reduces the need for chemical controls.

1. Quarantine

It follows that, since a majority of pests and diseases are introductions to Australia, the prevention of introduction of new pests is a priority for the nation. It would seem that federal governments have been less than diligent in their approach to quarantine yet the community is demanding reductions in pesticide use. Logic has it that a strong quarantine service would be repaid many times by the reduction in resources that need to be allocated to the research, extension and implementation that has to be mobilised to cope with an outbreak of a new pathogen, weed or insect.

Australia is indeed fortunate that it is a continent separated from the rest of the world by vast distances over water. This isolation is increasingly under threat with the increased international traffic. Recent governments have, at the same time, downgraded the quarantine services when logic would suggest that the opposite should occur. The cost of such a service has been an ongoing argument yet it is really an investment in the future and for the public good.

Whilst there have not been major outbreaks of pests and diseases of devastating proportions, the ongoing threat of blue tongue, foot and mouth disease and other exotic pests exists with substantial implications for international trade. Complacency by successive governments on this issue is unacceptable.

2. Monitoring

A coordinated program of monitoring of environmental indicators needs to be established and be under the control of a government agency or an independent body. This monitoring program needs to be addressed at three levels: the users, the environment and the produce. Although this would appear to be a policeman-like approach, it should be seen as part of a quality assurance program and early intervention. Whilst these activities are already in existence to a greater or lesser extent, there is little coordination nor an holistic approach.

The regular monitoring of pesticide users for blood pesticide levels would provide early warning signs for individuals that might help avert long-term exposure and the potential risks to health. The suggestion that pesticides should have markers present to make them more readily detectable warrants further debate.

A re-evaluation of the push by governments for export industries to take over residue testing of produce is needed. Testing services need to be at arms length from industry bodies for credibility in the market. Self-accreditation has only limited value in this regard, despite the obligations created for producers.

3. Research support by governments

Although pesticide and technology development are to a large extent the purvey of private industry, the issue of alternatives to pesticides, biological control, IPM and to some extent new varieties, has a strong element of public good. Given that most pests and diseases are introductions to Australia, their natural predators are likely to be absent unless accidentally or deliberately introduced. This research area is unlikely to be of commercial interest to the corporate sector yet remains an important option for limiting pesticide use. Considerable evaluation of potential control agents needs to be undertaken before introduction to minimise any risks, such as has occurred with the cane toad, for example. The prospects of success are not high yet those that are developed mostly justify the investment with a benefit: cost ratio in excess of 20:1. It is acknowledged that a number of cooperative research centres have biological control programs. However, governments must continue to support this area.

The evolving farming systems where, for example, crop residues are increasingly being retained (Chapter 4) may provide opportunities for use of allelopathic interactions to achieve weed control (e.g. Kirkegaard *et al.* 1996; An *et al.* 1998; Wu *et al.* 1998) and should be explored further.

8 RESEARCH AND DEVELOPMENT

In plant and animal protection there is an ongoing need for research to enable productivity enhancement, quality improvement, refinement of pesticide use and environmental sustainability. Several prospects for major advances exist, although the following list is not exhaustive.

Weed biology. For any IPM strategies to be effective the biology and ecology of the pests must be well understood. Continued support for these detailed studies must be assured.

Resistant varieties. Pesticide inputs can be reduced where the varieties of crop or pasture have genetic resistance to the pest. This has been a successful practice with rust resistance in cereals and to a lesser extent with blackleg control in canola where traditional breeding techniques have been common. Genetic engineering allows us to extend the scope and provide varieties resistant to insects and other pathogens and must be considered a desirable outcome, provided the safeguards are in place, as discussed. Herbicide resistant varieties create a new dimension and may or may not reduce herbicide inputs but may allow a more desirable chemical to be used.

Research funding must continue in order to provide resistant varieties in the quest for pesticide reductions. At the same time, companies must accept a greater responsibility for the stewardship of varieties and chemicals in their portfolios to ensure that sustainable practices are encouraged.

Spatial variability. Weed, disease and pest incidence does not occur uniformly in a field. The ability to map the incidence and to detect these early through remote sensing technology will enable controls to be implemented and best management practices to be developed. Such detection, in conjunction with global positioning system (GPS) technology, will enable better targeting of chemical and non-chemical options for pest management. The benefits to the environment and in input costs from improved target application and reduced pesticide use will be substantial.

The use of these technologies will also enable mapping at a regional level for impact assessment of management practices.

Crop monitoring. The cotton industry has shown the lead in the implementation of crop monitoring techniques. Whereas in the 1980s, up to 11 applications of insecticide were regularly applied to the crop to control *Heliocoverpa* spp., research into chemical group rotation, economic damage thresholds, host plant resistance, beneficial insects and cultural operations has enabled integrated pest management to achieve significant reductions in insecticide use. Similar studies need to be conducted for other pests throughout the agricultural sector to achieve similar ends. There is still a paucity of knowledge on economic thresholds of weeds, pests and diseases and the consequences of not controlling subthreshold levels on subsequent crops. Such data are fundamental to any impact assessment and for community education.

Waste disposal. Two of the most critical problems that need to be addressed are the disposal of old pesticides and hazardous wastes and the management of pesticide containers. It remains a question as to whether the protocols for these issues should be the responsibility of governments or a requirement in the registration process for the proponent. The agricultural chemical industry, through Avcare, has started to address this issue.

Integrated pest management. The development of IPM is critical for the sustainability of crop and pasture production. The issues of resistance, residues and community health reinforce the need to embrace all techniques for pest management. This will require a continuous and coordinated research effort in order to harness the potential of IPM. A necessary component will be the ongoing search for biological control agents, particularly for the extensive agricultural systems.

The economic basis must be understood to ensure farmers can identify the benefits and afford the implementation of IPM. There needs to be a change from short-term control to long-term management strategies.

9 CONCLUSIONS

The concerns of the community about pesticide use are real and understood. The agricultural industry is addressing the issues rationally and positively through research, education and application of new technologies as well as at policy level. If food production needs world-wide are to be met, and farmers individually are to survive financially, pesticide use will be a part of an IPM system for a long time to come. Provided they are used efficiently and safely the consequences will be minimal. It is important, however, for the intentions of the industry to be clearly disseminated, for accurate records of pesticide usage to be maintained and for the accountability to be defined.

It is the responsibility of governments to ensure the appropriate legislative protection and to maintain vigilance with respect to quarantine and residue monitoring. The appointment of Australia's first Chief Plant Protection Officer (DPIE 1998) is a positive step to this end.

It is the responsibility of the chemical industry to ensure through the duty of care identified in the Helix litigation (Long 1998) that information on all aspects of their chemicals is widely disseminated. It is also important that companies have greater stewardship of their products in the agroecosystem.

It is the responsibility of all chemical users to be appropriately credentialled, and to use any chemicals within best practice guidelines.

REFERENCES

An, M., Pratley, J.E., Haig, T.M. (1998). Allelopathy: from concept to reality. *Proceedings of the 9th Australian Agronomy Conference*, pp. 563–566, Wagga Wagga, NSW.

Australian Bureau of Agricultural and Resource Economics (1994). Commodity Statistical Bulletin 1994, p. 102, ABS Canberra.

Avery, D.J. (1998). The importance of high farm yields to wildlife conservation. *Proceedings 9th Australian Agronomy Conference*, pp. 85–91, Wagga Wagga, NSW.

Banyer, R.J., and Cuthbertson, E.G., Slater, P.D. (1994). Crop Protection, In: Pratley, J.E. (ed.) *Principles of Field Crop Production*, 3rd ed., pp. 390–463. Sydney University Press: Sydney.

Beckie, H., Friesen, L., Nawoisky, K., and Morrison, I. (1990). A rapid bioassay to detect trifluralin-resistant green foxtail (*Setaria viridis*). *Weed Technology* **4**: 505-8.

Behm, C.A., and Bryant, C. (1985). The modes of action of some modern anthelmintics, In: Anderson, N., Walter, P.J. (eds) *Resistance in Nematodes to Anthelmintic Drugs*, pp. 57–68. CSIRO, Melbourne.

Blair, A., and Zalun, S.H. (1995). Agricultural exposures and cancer. *Environmental Health Perspectives* **103**(8): 205–208.

Bowmer, K.H. (1972). Aspects of the long term use of herbicides: measurement of residues of diuron and simazine in an orchard soil. *Australian Journal of Experimental Agriculture and Animal Husbandry* **12**: 535.

Bradshaw, L.D., Padgette, S.R., Kimball, S.L., and Wells, B.H. (1997). Perspectives on glyphosate resistance. *Weed Technology* **11**(1): 189–198.

Brown, A.N.A. (1967). Genetics of insect vectors of disease, In: *Boophilus microplus: The Common Cattle Tick*. Springer-Verlag, New York.

Carson, R. (1962). *Silent Spring*. Houghton Mifflen, Boston US.

Constable, G.A., Llewellyn, D.J., and Reid, P.E. (1998). Biotechnology risks and benefits: the Ingard cotton example. *Proceedings of the 9th Australian Agronomy Conference*, pp. 92–98, Wagga Wagga, NSW.

CRC for Weed Management Systems (1995/96). Annual Report. University of Adelaide, Australia.

Department of Primary Industries and Energy (1998). New plant health initiative. Media Release DPIE 98/67A.

Dobson, R.J., Le Jambre, L., and Gill, J.H. (1996). Management of anthelmintic resistance: inheritance of resistance and selection for drug use. *International Journal of Parasitology* **26** (8/9): 993–1000.

Duke, S.O. (1995). Herbicide resistant crops: a new approach to an old problem or a radical new tool, In: McLean, G.D., and Evans, G. (eds) *Herbicide Resistant Crops and Pastures in Australian Farming Systems*, pp. 41–52. Bureau of Resource Sciences, Canberra.

Ferris, I.G., and Haigh, B.M. (1993). Herbicide persistence and movement in Australian soils: implications for agriculture, In: Jack Altman (ed.) *Pesticide interactions in crop production*. CRC Press, London.

Ferris, I.G., Felton, W.L., Holland, J.F., and Bull, M.S. (1989). Effect of tillage practice on the persistence of atrazine in two contrasting soils in northern NSW. *Australian Journal of Experimental Agriculture* **29**: 849–853.

Fishpool, K.I., Garland, P.J., and Greening, H.G. (1975). Farm cleanup and fumigation to control insect pests. *Agriculture Gazette of NSW* **88**: 33–35.

Fordyce, G., Howett, D.J., Holroyd, R.G., O'Rourke, P.K., and Entwistle, K.W. (1996). The performance of brahman-shorthorn and Sahiwal-shorthorn beef cattle in the dry tropics of northern Queensland: ectoparasite resistance. *Australian Journal of Experimental Agriculture.* **36**:9-17.

Forget, F. (1991). Pesticides and the third world. *Journal of Toxicology and Environmental Health* **32**: 11–31.

Forrester, N., Buerger, P., Gunning, R., Gibb, D., Pyke, B., and Wilson, L. (1997). Insect resistance management strategy for conventional cotton 1997–98, In: Shaw, A.J., and Harris, W. (eds), *Cotton Pesticides Guide 1997–98*, NSW Agriculture Agdex 151/680.

Fremlin, R.R.A. (1989). At issue — herbicides in forest management in Western Australia, In: *Persistence of Herbicide Residues in Soil in Wheat Cropping Systems in Australia*, p. 3. Proceedings of the 3rd National Workshop, Melbourne.

Gill, G. (1995). Development of herbicide resistance in annual ryegrass (*Lolium rigidum*) populations in the cropping belt of Western Australia. *Australian Journal of Experimental Agriculture* **35**: 67–72.

Gill, G., Piper, T., Martin, B., and Pannell, D. (1991). *Herbicide Resistant Weeds.* Western Australian Department of Agriculture, Bulletin 4212.

Gray, G.D. (1997). Novel approaches to internal parasite control. *Proceedings of the 4th International Congress of Sheep Veterinarians*, Armidale, pp. 64–69.

Gressel, J. (1990). Need herbicide resistances have evolved? Generalizations from around the world. *Proceedings of the 9th Australian Weeds Conference* Adelaide: pp. 173–184.

Gressel, J., and Segal, L. (1990). Modelling the effectiveness of herbicide rotations and mixtures as strategies to delay or preclude resistance. *Weed Technology* **22**(4): 180–96.

Grieshop, J.L., Villanueeva, N.E., and Stiles, M.C. (1994). Wash day blues: Second hand exposure to agricultural chemicals. *Journal of Rural Health* **10**(4): 247–257.

Groves, R.H. (1998). *Recent incursions of weeds to Australia 1971–1995.* CRC for Weed Management Systems Technical Series No. 3.

Hall, E. (1990). Reasons for breakdowns in worm control programs. *Sheep Medicine Proceedings***141**: 247–253.

Hassell and Associates Pty Ltd. (1995). *The domestic market for Australian organic produce.* Rural Industries Research and Development Corporation, Canberra.

Heap, I.M. (1997) The occurrence of herbicide resistant weeds worldwide. *Pesticide Science* **51**: 235.

Heap, J., and Knight, R. (1982). A population of ryegrass tolerant to the herbicides diclofop-methyl. *Journal of the Australian Institute of Agricultural Science* **48**: 156–157.

Hole, S.J.W., and Powles, S.B. (1997). Reduced efficacy and enhanced degradation of carbetamide after repeated application in Australia. *Weed Research* **37**: 165–170.

Holford, I.C.R., Haigh, B.M., and Ferris, I.G. (1989). Atrazine persistence and phytotoxicity on wheat as affected by nitrogen and rotation-induced changes in soil properties. *Australian Journal of Agricultural Research.* **40**: 1143–1153.

Holroyd, R.G., Dunster, P.J., and O'Rourke, P.K. (1988). Effects of cattle tick (*Boophilus microplus*) infestations on performance of *Bos indicus* cross cows and their progeny. *Australian Journal of Experimental Agriculture* **28**: 1–9.

Holt, J., and LeBaron, H. (1990). Significance and distribution of herbicide resistance. *Weed Technology* **4**: 141–149.

House of Commons Agriculture Committee (1987). *The effects of pesticides on human health — Second Special Report.* Vol. I. London. Her Majesty's Stationery Office.

Howat, P.D. (1987).Weeds resistant to herbicides in Australia and contributing factors leading to their appearance. *Plant Protection Quarterly* **2**: 82–85.

International Agency for Research on Cancer (IARC) (1991). Occupational exposure to pesticides, In: IARC Monographs Vol.53, pp. 45–91. World Health Organisation.

Johnson, D.W., Kish, L.P., and Allen, G.E. (1976). Field evaluation of selected pesticides on the natural development of the entomopathogen *Nomuaea rileyi* on the velvetbean caterpillar in soybean. *Environmental Entomology* **5**: 964–6.

Johnstone, P., Minchinton, I., Amor, R.L., Code, G., and Incerti, M. (1986). The long term persistence effects of trifluralin, chlorsulfuron and diclofop-methyl in three Victorian soils, In: *Persistence of Herbicide Residues in Soil in Wheat Cropping Systems in Australia. Proceedings 1st National Workshop*, Rutherglen.

Jutsum, A., and Shaner, D. (1992). Herbicide resistance: the stance of the agrochemical industry. *Proceedings 1st International Weed Control Congress*, Melbourne **2**: 244–246.

Kent, J.H. (1998). Implementation of the Communication Strategy. Report to Department of Primary Industry and Energy. Farmcare Australia.

Kieran, P.J. (1994). Moxidectin against ivomectin-resistant nematodes: a global view. *Australian Veterinary Journal* **71**(1): 18–20.

Kirkegaard, J.A., Wong, P.T.W., Desmarchelier, J.M., and Sarwar, M. (1996). Suppression of soil-borne cereal pathogens and inhibition of wheat germination by mustard seed meal. *Proceedings 8th Australian Agronomy Conference*, Toowoomba, 353–356.

Kristensen, P., Anderson, A., Irgens, L.M., Laske, P., and Bye, A.S. (1996). Incidence and risk factors of cancer among men and women in Norwegian agriculture. *Scandanavian Journal of the Work Environment* **22**:39–50.

Lacey, E. (1985). The biochemistry of anthelmintic resistance, In: Anderson, N., and Walter, P.J. (eds) *Resistance in Nematodes to Anthelmintic Drugs*, pp. 69–78. CSIRO, Melbourne.

Landrigan, P.J., Graham, D.G., and Thomas, R.D. (1994). Environmental neurotoxic illness: research for prevention. *Environmental Health Perspectives* **102**(2):117–20.

Le Jambre, L.F. (1993). Ivomectin resistant *Haemonchus contortus* in Australia. A*ustralian Veterinary Journal***70**(9): 357.

Lemerle, D., Verbeek, B., Cousens, R.D., and Coombes, N.E. (1996). The potential for selecting wheat varieties strongly competitive against weeds. *Weeds Research* **36**: 505–513.

London, L., and Myers, J.E. (1995). Critical issues for agrichemical safety in South Africa. *American Journal of Industrial Medicine* **27**: 1–14.

Long, P. (1998). The liability of agronomists in the light of the Helix litigation. *Proceedings 9th Australian Agronomy Conference*, Wagga Wagga, NSW.

Luck, J.E., Gillings, M.R., and Steel, C.C. (1995). Rapid detection of benzimidazole-resistant *Botrytis cinerea* in the vineyard. *Australian Grapegrower and Winemaker*, Annual Technical Issue, pp. 122–125.

Mangels, G. (1991). Behavior of the imidazolinone herbicides in soil — a review of the literature, In: Shaner, D.L., O'Connor, S.L. (eds) *The imidazolinone herbicides*, pp.191–209. CRC Press, Boston.

Maroni, M., and Fait, A. (1993). Health effects in man from long-term exposure to pesticides — a review of the 1975–1991 literature. *Toxicology* **78**: 1–180

Matthews, J., and Powles, S. (1992). Aspects of the population dynamics of selection for herbicide resistance in *Lolium rigidum* (Gaud). *Proceedings 1st International Weed Control Congress*, Melbourne **2**: 318–320.

McGowan, A.A. (1970). Comparative germination patterns of annual grasses in north-eastern Victoria. *Australian Journal of Experimental Agriculture and Animal Husbandry* **10**: 401–4.

Milham, N., and Davenport, S. (1994). NSW Agriculture submission to the Prices Surveillance Authority Inquiry into the Price of Farm Chemicals. Economic Policy Report No.5. NSW Agriculture, Orange.

Miller, C.S. (1996). Chemical sensitivity: symptom, syndrome or mechanism for disease? *Toxicology* **111**: 69–86.

Millis, N.F. (1995). Herbicide resistant crops: what should be Australia's position, In: McLean, G.D. , Evans, G. (eds) *Herbicide resistant crops and pastures in Australian farming systems*, pp.1–6. Bureau of Resource Sciences, Canberra.

Moody, H. (1997). Coping with fungicide resistance. *Australian Horticulture* **95**(1): 424.

Mullen, C.L., and Dellow, J.J. (1998). *Weed control in winter crops 1998*. NSW Agriculture Agdex 100/682.

Nair, N.G., and Holley, M. (1991). *Disease management of bunch rot of grapes*, NSW Agriculture.

National Registration Authority for Agricultural and Veterinary Chemicals (1996a). *Veterinary Manual — the Requirements Manual for Veterinary Chemicals*, NRA, Canberra.

National Registration Authority for Agricultural and Veterinary Chemicals (1996b). *Agriculture Manual — the Requirements Manual for Agricultural Chemicals*, NRA, Canberra.

National Registration Authority for Agricultural and Veterinary Chemicals (1997). *Existing chemicals review program*. Review of Endosulfan. Draft NRA: Canberra.

National Registration Authority for Agricultural and Veterinary Chemicals (1998). NRA Review of Endosulfan Draft, NRA, Canberra.

Neutra, R.R. (1990). Counterpoint from a Cluster Buster. Reviews and commentary. *American Journal of Epidemiology* **132**(1): 1–8.

Nolan, J. (1986). Insecticide resistance in veterinary ectoparasites. *Parasitology Today*, Australian Supplement July: pp. 18–19.

O'Brien, R.G., Glass, R.J., and Vawdrey, L.L. (1988). Fungicide resistance in cucurbit powdery mildew (Sphaerotheca fuliginea) and its effect on field control. *Australian Journal of Experimental Agriculture* **28**(3): 417–23.

O'Brien, R.G., Hutton, D.G., and Vawdrey, L.L. (1989). Fungicide resistance and its management. *Queensland Agriculture Journal* **115**(1): 13–15.

Osborne, G.J., and Donohoe, T.M. (1977). Residual levels of paraquat in a red earth soil after 7 years of minimum and reduced cultivation. *Journal of the Australian Institute of Agricultural Science* **43**(3 & 4): 169.

Osteen, C.D., and Szmedra, P.I. (1989). *Agricultural Pesticide Use Trends and Policy Issues*. US Department of Agriculture, Economic Research Series, Agricultural Economics Report No. 622, Washington DC.

Penrose, L.J. (1989) A rational approach to apple scab control – the role of disease warning systems and curative spraying. *Plant Protection Quarterly* **4**: 115–118.

Pimental, D., and Greiner, A. (1997). Environmental and socio-economic costs of pesticide use, In: David Pimental (ed.) *Techniques for Reducing Pesticide Use*, pp. 51–78. Wiley: UK.

Powles, S. (1987). A review of weeds in Australia resistant to herbicides. *Proceedings 8th Australian Weeds Conference*, Sydney: 109–113.

Powles, S.B, and Howat, P.D. (1990). Herbicide-resistant weeds in Australia. *Weed Technology* **4**: 178–85.

Powles, S., and Matthews, J. (1992). Multiple herbicide resistance in annual ryegrass (*Lolium rigidum*): a driving force for the adoption of integrated weed management, In: 1. Denholm, A., Devonshire, and Holloman, D. (eds) *Achievements and developments in combating pest resistance*. Elsevier Press, London.

Powles, S., Holtum, J., Preston, C., Burnet, M., Christopher, J., Matthews, J., Mansooji, A., Boutsalis, P., and Purba, E. (1991). *Herbicide resistance in Australian weeds: the present status, likely future developments and the need for management strategies*. Department of Crop Protection, Waite Agricultural Research Institute, University of Adelaide

Powles, S.B., Lorraine-Colwill, D.F., Dellow, J.J., and Preston, C. (1998). Evolved resistance to the herbicide glyphosate in rigid ryegrass (*Lolium rigidum*) in Australia. *Weed Science* (in press).

Pratley, J.E., Graham, R., and Leys, A. (1993). Determination of the extent of herbicide resistance in southern New South Wales. *Proceedings 10th Australian and 14th Asian-Pacific Weed Conference*, Brisbane **1**: 286–288.

Pratley, J.E., Lemerle, D., Luckett, D.J. Brennan, J.P., and Cornish, P.S. (1995). The role of herbicide resistant crops in the winter rainfall farming systems of south-eastern Australia, In: McLean, G.D., Evans, G. (eds) *Herbicide resistant crops and pastures in Australian farming systems*, pp.127–138. Bureau of Resource Sciences, Canberra.

Pratley, J., Baines, P., Eberbach, P., Incerti, M., and Broster, J. (1996). Glyphosate resistance in annual ryegrass. *Proceedings 11th Conference Grasslands Society of NSW*, p. 122.

Pye, V., and Kelly, J. (1984). The extent of groundwater contamination in the United States, In: NAS (ed.) *Groundwater contamination*, National Academy of Sciences, Washington DC.

Readshaw, J.L. (1971). An ecological approach to the control of mites in Australian orchards. *Journal Australian Institute of Agricultural Science* **41**: 226–230.

Rothman, K.J. (1990). A sobering start for the Cluster Busters' Conference. *American Journal of Epidemiology* **132**(1), Supplement 56–13.

Ryan, G.F. (1970). Resistance of common groundsel to simazine and atrazine. *Weed Science* **18**: 614–616.

Simpson, W.M. (1996). Agromedical highlights of the risk assessment issues for Sensitive Human Populations conference. *Journal of Agromedicine* **3**(1): 81–82.

Sogoff, M. (1988). On teaching a course on ethics, agriculture and the environment: part 2. *Journal of Agricultural Ethics* **1**(2): 87–100.

Staub, T., Sozzi, D. (1984). Fungicide resistance: a continuing challenge. *Plant Disease* **68**: 1026–31.

Steel, C.C. (1994). Grapevine fungicides — how they work and resistance problems. *Australian Grapegrower and Winemaker*, Annual Technical Issue, pp. 111–114.

Steel, C.C. (1996). Catalase activity and sensitivity to the fungicides, iprodione and fludioxonil in *Botrytis cinerea*. *Letters in Applied Microbiology* **22**: 335–338.

Steel, C.C., Nair, N.G. (1993). The physiological basis of resistance to the dicarboximide fungicide iprodione in Botrytis cinerea. *Pest Biochemistry and Physiology* **47**: 60–68.

Stone, B.F. (1968). Inheritance of resistance to organophosphorus acaricides in cattle tick. *Australian Journal of Biological Science* **21**: 309–319.

Tardiff, F.J., Preston, C., Powles, S.B. (1996). Mechanisms of herbicide multiple resistance in *Lolium rigidum*. *Proceedings International Symposium on Weed and Crop Resistance to Herbicides*. Kluwer Academic, Dordrecht, The Netherlands.

Thamsborg, S.M., Githigia, S.M., Larsen, M., Kyesgaard, N.C., and Nansen, P (1997). The effect of nematode destroying fungus *Duddingtonia flagrans* on natural nematode infections of grazing sheep. *Proceedings 4th International Congress for Sheep Veterinarians*, Armidale, pp. 391–397.

United States Environment Protection Agency (1997). *EPA Special report on endocrine disruption*. EPA Fact Sheet, pp. 1–120. Washington, DC.

Vaughn, K.C., Duke, S.O. (1991). Biochemical basis of herbicide resistance, In: Ebing, W. (ed.) *Chemistry of Plant Protection*. Springer-Verlag, Berlin.

Waller, P.J., Faedo, M. (1993). The potential of nematode phagus fungus to control free living larval stages of nematode parasites of sheep. *Veterinary Parasitology* **49**: 285–97.

Waterhouse, D., Carman, W.J., Schottenfield, D., Gridley, G., McLean, S. (1996). Cancer incidence in the rural community of Tecumseh, Michigan: a pattern of increased lymphopoietic neoplasms. *Cancer* **77**: 763–71.

Weisenburger, D.D. (1994). Epidemiology of non-Hodgkin's lymphoma: recent findings regarding an emerging epidemic. *Animal Oncology* **5**(1): 19–24.

Weiss, P.W. (1964). Soil residues of herbicides. MSc Thesis, University of NSW.

Whitten, M.J., Maddern, R.H. (1993). The theory of genetic control and development of strains useful in the genetic control of the sheep blowfly, In: *Sheep Blowfly and Flystrike in Sheep*, 2nd National Symposium, Sydney, pp. 253–61.

Willadsen, P., Williams, P.G. (1979). The relationship between skin histamine concentrations and the resistance of cattle to the tick (*B. microplus*). *International Journal of Parasitology* **8**: 89–95.

Wu, H., Pratley, J., Lemerle, D. (1998). Differential allelopathic potential among wheat accessions to annual ryegrass. *Proceedings 9th Australian Agronomy Conference*, pp. 567–571. Wagga Wagga, NSW.

Yaacoby, T., Schonfeld, M., Ruben, B. (1986). Characteristics of atrazine resistant biotypes of three grass weeds. *Weed Science* **34**: 181–184.