Agricultural Biotechnology: Herbicide Tolerant Crops in Australia

BUREAU OF RURAL SCIENCES
BRS
AUSTRALIA

BIOTECHNOLOGY AUSTRALIA
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Foreword

Australian agricultural industries have a history of readily adopting scientific advances to improve their competitiveness and sustainability. The newest scientific advance affecting the agricultural industries is biotechnology. Biotechnology is being used to develop new plant varieties. Currently, the plants are mainly herbicide tolerant crops or crops with resistance to insects or disease. Future developments are expected to involve changes to the nutritional characteristics of plants, such as decreasing harmful fats in oils produced by plants, and making crops more tolerant to adverse environmental conditions such as drought, salt or waterlogging. Other prospects include plants that produce pharmaceuticals, industrial chemicals and new fibres and fuels.

The prospect of the new crops, and the new technology being used in Australian agriculture and entering the food chain has raised a number of issues. These range from questions about the potential environmental and production benefits to the safety of the technology and its products to ethical questions about ‘interfering with nature’. Debate on some issues will be informed by analysis of the possible consequences of the technology on human health, the environment, the sustainability of agriculture, society or sections of society, and on the competitiveness of Australian agriculture, while other issues are less amenable to scientific analysis.

The recent introduction of herbicide tolerant cotton and applications for commercial release of GM canola in Australia make this a timely publication. It examines herbicide tolerant crops, particularly genetically modified (or transgenic) herbicide tolerant crops, the reasons they are being developed and the rationale behind their use by farmers. The benefits and risks from growing these crops are examined, along with the strategies used to manage the risks. The aim is to inform the public debate about the technology and its potential in Australian agriculture.

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Executive Summary

Informed debate about herbicide tolerant GM crops

This is a review of the introduction of herbicide tolerance into a variety of crops through genetic engineering and the use of those crops in agricultural practice. The report is directed to a general audience interested in understanding the scientific background to the new technology and intends to contribute to the public debate on genetically modified organisms.

The estimated global area of GM crops in 2001 was 52.6 million hectares with the four principle crops being soybean, cotton, canola and corn. The crops incorporate a number of different traits, with the main commercial trait so far being herbicide tolerance. In 2001, herbicide tolerant GM crops accounted for about 77% of the global area of commercially grown GM crops and herbicide tolerance was the most common GM trait trialled in the field.

Herbicide tolerance can be introduced into crops by genetic modification or by traditional breeding methods. Genetically modified herbicide tolerant cotton has been commercialised in Australia. There are also two types of herbicide tolerant canola available in Australia that are not genetically modified. They are Clearfield or ‘imi’ tolerant canola and triazine tolerant (TT) canola. Two conventionally bred ‘imi’ tolerant wheat varieties are also available in Australia.

Genetically modified herbicide tolerant canola will probably be Australia’s next transgenic crop and has undergone field trials in Australia. The Office of the Gene Technology Regulator is currently processing two applications to grow this type of canola commercially. A decision is expected in 2003.

Weeds – a problem in agriculture

Herbicide tolerance is popular because weeds are a huge problem in agriculture. Weeds have been estimated to cost more than $3.5 billion annually in Australia. Traditional weed control used manual methods such as hand weeding or hoeing. These methods are now mechanised and often involve ploughing before sowing. The fragile soils in Australia make this a less than ideal method and, since the 1970s, conservation farming using herbicides for weed control has been introduced. Herbicide tolerant crops make conservation farming easier.

Herbicide tolerant crops are being developed to improve weed control and the productivity of farming systems. The benefits to farmers can be grouped into improved weed control, increased management options

Benefits of herbicide tolerance …

and environmental benefits. The community as a whole can also benefit from the commercial advantages in developing, producing and selling the seeds and the technology, from the increased farm productivity and from the environmental benefits. The relative economic benefits to farmers of the GM herbicide tolerant crops are not clear, with some farmers finding them profitable and others finding them less so. The relative profitability also varies with the season and the existing weed problems. The main reason farmers are using the GM herbicide tolerant crops is that they make weed control easier.

… and potential risks

This report discusses potential risks from herbicide tolerant crops and how these risks are being managed. Some of these risks are specific to GM herbicide tolerant crops, and others exist with herbicide tolerant crops developed by all methods. If not managed effectively, herbicide tolerant crops could add to weed problems, particularly herbicide resistant weed problems. It has been found that herbicide tolerance can be transferred between plants by cross-pollination, but the likelihood of this happening depends on many factors including the proximity of closely related weedy relatives. Whether a herbicide tolerance gene transferring to a weed increases weed problems depends on the gene, the herbicide use patterns and on alternative weed management strategies available.

Other risks have also been proposed including risks to human health and commercial risks with some markets requiring non-GM products. All current evidence points to no adverse effects on animals, humans, or the environment from eating approved GM crops but some consumers are still concerned.

The effect of GM crops on sustainable agriculture

The impact of GM herbicide tolerant crops on Australian agriculture will depend on how the crops are used in the field and how international markets receive the products from these crops. Risk management today is not just a process of governments making decisions; it also requires individuals, businesses and industries to manage some of the risks. Government assessments can ensure that only safe GM crops are used and other strategies can be employed within industries to ensure the crops deliver maximum benefits to producers and the Australian agricultural environment. These strategies may include refuges, buffer crops, integrated pest management and other activities such as weed management and pesticide use on individual farms, in catchments or in regions. By working together and managing all the risks, GM herbicide tolerant crops have the potential to enhance the contribution of Australian agriculture to ecologically sustainable development.

Contents

Introduction

Farmers have been improving their animal and plant stocks for many generations. For breeding the next generation, breeders have selected animals and plants with higher production, better disease resistance, and are more suited to local conditions. Advances in biological sciences in the last century and the application of the resultant technologies to agriculture are allowing improvements in agricultural stock to develop much more rapidly. 'Gene technology' (see Glossary for definitions of terms) enables characteristics to be shifted between unrelated organisms through the transfer of genes.

The first generation of agricultural biotechnology has reached commercial application and is focused on the introduction of insect and disease resistance and herbicide tolerance into crops. More recent research has involved changes to the nutritional characteristics of plants, such as decreasing the harmful fats in oils produced by plants, and making crops more tolerant to adverse environmental conditions such as drought, salt or waterlogging. Future prospects include plants that produce new products such as pharmaceuticals, industrial chemicals and new fibres and fuels. Other applications include using plants to remove toxic chemicals from degraded areas (phytoremediation) and the use of plants to recover heavy metals from soils for economic profits (phytomining). Genetic modification of animals is more controversial and further from commercialisation than developments in plant biotechnology.

The main characteristic tested in the first generation of trials of genetically modified plants was herbicide tolerance. Herbicide tolerant plants accounted for 40 per cent of field trials between 1986 and 1992, the next largest group being trials of markers to identify the altered plants. The popularity of herbicide tolerance is not surprising when we consider the improvements to weed control options the trait could provide and the fact that weeds are estimated to cause more damage to agriculture than all other pests. Herbicide tolerance is also useful as a marker that identifies successfully transformed plants.

Transgenic herbicide tolerant crops are those that contain genes from other species such as bacteria so the plants are tolerant to particular groups of herbicides. They have been researched and tested in many countries and are now grown commercially in some, mainly American, countries. In Australia, two varieties of carnations developed for blue colour and long life, but which are also herbicide tolerant, have been grown commercially for some years. Also, three cotton varieties, have been commercialised - insect resistant cotton, herbicide tolerant cotton and a variety that contains both traits.

This volume explores weeds and their control in Australian agriculture and how herbicide tolerant crops could improve weed control. The potential benefits and risks of herbicide tolerant crops and how the risks could be managed to benefit Australian agriculture and the community are also covered. While the focus is on herbicide tolerant crops developed by genetic modification, many of the issues also apply to herbicide tolerant crops developed by more traditional methods.

1. Weeds and weed control in Australian agriculture

Weeds

Weeds are plants growing where they are not wanted. They have a potentially detrimental effect on economic, social and conservation values. About half of the 1 900 vascular plant species introduced into Australia since European settlement are now regarded as weeds. Of the more than 220 species declared as noxious weeds in Australia, 46 per cent were introduced intentionally for other purposes and 31 per cent as ornamental plants (Parsons and Cuthbertson 1992). In some circumstances important grazing plants, such as annual ryegrass, are significant weeds in crops. Native plant species can also be weeds when they establish in regions outside their natural habitat or increase in abundance as a result of human disturbance.

In agriculture, weeds compete with crop and pasture plants for light, water and nutrients; they contaminate grain, fodder and animal products and poison livestock. Estimates on the costs of weeds in agriculture vary, but one estimate puts the direct financial impacts of weeds on agriculture at $3.5 billion a year – covering both loss of production and control costs (Plant Health Australia, 2002). This is greater than the estimated damage from all other agricultural pests.

Weed control

Weed control in early agricultural systems was, and in some cases still is, done manually by hand weeding and hoeing. In developed countries it became mechanised with the development of agricultural machinery late last century, when ploughing before seeding became a major method of weed control. The introduction of herbicides and developments in machinery technology in the 1970s allowed the development of no-till and conservation tillage techniques. These techniques replace tillage (ploughing) for weed control with herbicides, which reduces mechanical intervention with the soil and loss of soil carbon to the air. With no-till systems the only time the soil needs to be disturbed is when a crop is sown (Bos *et al.* 1995).

Conservation farming techniques are particularly important in Australia, with our fragile soils. Farmers have on the whole been keen to adopt these methods to conserve soil and reduce soil erosion. Another feature of the conservation farming systems is the move away from continuous wheat cropping to rotations of a range of summer and winter crops. The rotations are designed to maintain soil fertility, control disease, maximise the use of rainfall and reduce run-off and soil erosion (Bos *et al.* 1995, Fawcett *et al.* 1994). There is a strong correlation between the adoption of reduced tillage cropping systems and increased herbicide use (Powles 1999).

The Commonwealth, State and Territory Ministers responsible for agriculture, forestry and the environment have developed a National Weeds Strategy to reduce the impact of weeds on the sustainability of Australia’s productive capacity and natural ecosystems. The Strategy has three goals: to prevent the development of new weed problems; to reduce the impact of existing weed problems of national significance; and to provide the framework and capacity for managing weed problems of national significance. The Strategy addresses weeds of national significance, which includes weeds that threaten the profitability or sustainability of Australia’s principal primary industries, weeds that threaten conservation areas or environmental resources of national significance or which constitute major threats to Australia’s biodiversity, and those weed problems that may require remedial action across several States and Territories. The National Strategy provides a framework for coordinating weed management activities across Australia (www.weeds.org.au).

Herbicides

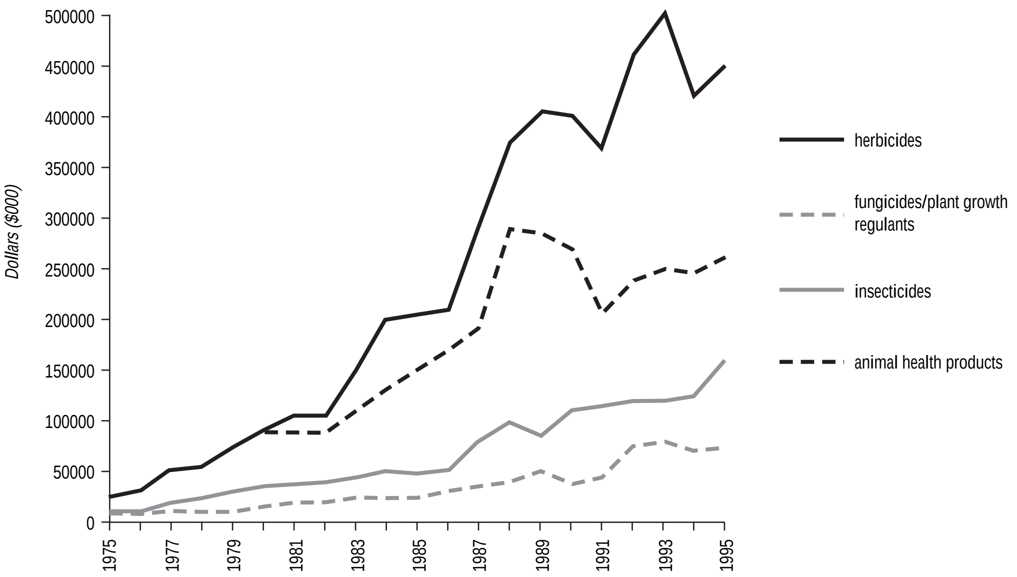
Herbicides are phytotoxic chemicals (that is, plant poisons) used to kill weeds. There are many types of herbicides. For example, probably the best-known herbicide in Australia is glyphosate (sold as Roundup, or Zero,), which is used for broad-spectrum weed control in a variety of crops, home gardens and forests. Broad-spectrum herbicides kill a wide range of plants, whereas selective herbicides kill a narrower range of plants, at particular stages of development. For example, herbicides such as dicamba kill broadleaf weeds but not grasses. Some herbicides are short-acting and others are residual. Broad-spectrum herbicides are generally applied prior to the emergence of crops, due to their lethal effect on most plants, including the crop. Selective herbicides can be used after the crop has begun to grow, providing they do not damage the crop.

Herbicides with the same mode of action are classified into groups. A list of the herbicide groups, their principal modes of action, the chemical families on which they are based and common trade names is in Appendix 1. Recently it has become apparent that herbicides with the same mode of action can, if used repeatedly on the same area, greatly increase the risk of weeds developing resistance to those herbicides. Herbicide use strategies are implemented to minimise the risk of resistance.

Herbicide use

The world consumption of pesticides has grown markedly since the 1960s, with production increasing tenfold from 1955 to 1985. Although use levelled off in the early 1990s, it has since resumed its growth and the volume of pesticides used is currently rising at about 1 per cent per year (World Resources Institute 1998). In 1995, world pesticide consumption reached 2.6 million tonnes of ‘active ingredients’, the biologically active chemicals, with a market value of US$38 billion. Roughly 85 per cent of this was used in agriculture. About 75 per cent of pesticide use occurs in developed countries, mostly in North America, Western Europe and Japan. In these regions the pesticide market is dominated by herbicides (World Resources Institute 1998). In Australia, herbicides currently represent about 70 per cent by value of the sales of agricultural chemicals, excluding animal health care products (Figure 1).

Figure 1: Australian agricultural and veterinary chemicals sales (1987/88 dollars)



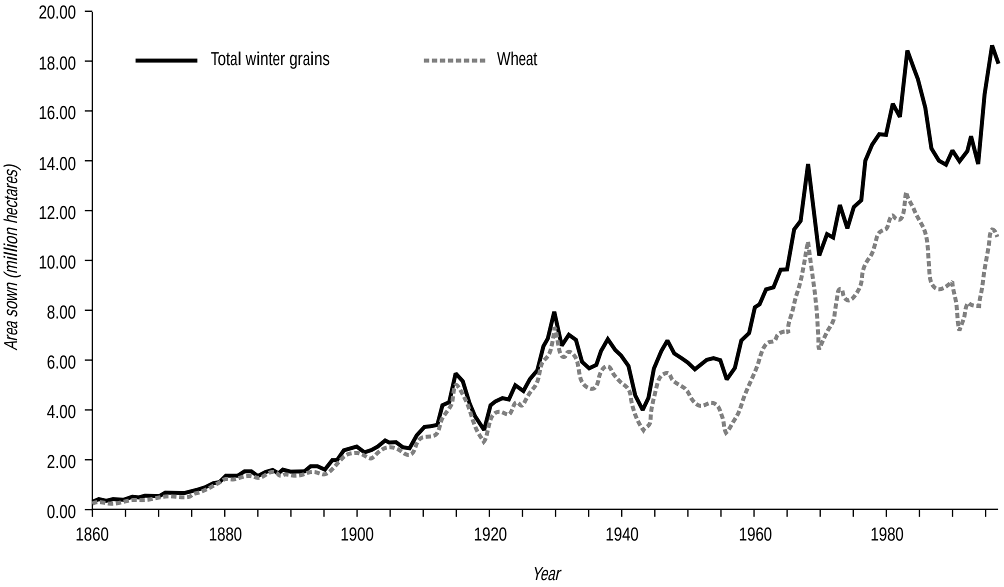
Source: Rowland and Bradford 1998

The value of herbicide sales in Australia has increased more than fivefold since 1980. Australian farmers have become very dependent on herbicides for profitable crop production, particularly since introducing 'conservation farming' techniques designed to reduce soil erosion (Pratley *et al.* 1998). An example of increased herbicide use is in the cropping areas of Western Australia where the area under crops has remained more or less constant throughout the 1980s, at about 5 million hectares, while the area treated with herbicide has increased from 3.9 to 9.5 million hectares through multiple applications (Gill 1995).

Improvements in weed control technology, particularly the new and growing range of herbicides and the engineering of machinery for minimum tillage, has played an important part in the growth of the area used for cropping in Australia. The area of winter grains (wheat, barley, oats, triticale, canola, lupins, field peas, chickpeas, faba beans, lentils and vetch) and wheat sown in Australia since 1860 is shown in Figure 2. The area planted to winter grains almost doubled between the early 1960s and the late 1980s, with a peak of 18 million hectares in 1983/84 (McLean and Evans 1996). This was not exceeded until 1996, following the drought of 1994/95, when the area planted to winter grains reached 18.6 million hectares.

This growth in production was achieved by expansion into new areas and by shortening the pasture phase of rotations, both activities helped by herbicide use.

Figure 2: Area of winter grains and wheat sown in Australia since 1860



Source: J. Walcott, Bureau of Rural Sciences, personal communication

There is now increasing international pressure to change the way agricultural chemicals are managed to minimise the risks to human health, the environment and trade from the use of these chemicals. The new, high level Agricultural and Veterinary Chemical Policy Committee (AVCPC) was established by the Primary Industries Standing Committee in mid 2001 to provide the national strategic policy framework for the management of agricultural and veterinary (agvet) chemicals in Australia.

AVCPC has developed a risk management framework to provide the basis for the development of policies and strategies for ensuring the ongoing effectiveness of Australia's agvet chemical management system, building upon the key issues identified by the National Strategy for the Management of Agricultural and Veterinary Chemicals, published by the former Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ). The risk management framework identifies and prioritises the AVCPC action necessary to ensure that the risks agvet chemical use presents to human health and the environment, including the risks to trade, and the risks to the benefits that accrue to industry and the community from the use of agvet chemicals, are effectively managed.

AVCPC is concentrating its work, initially, on four priority policy areas – appropriate chemical access, agvet chemical user awareness and training, market access and system performance.

One technological development that will change herbicide use and, perhaps, increase agricultural productivity is the introduction of herbicide tolerant crops.

2. Herbicide tolerant crops

There are two ways of developing a herbicide which kills weeds but does not affect crops. The first is to find chemicals which kill only the weeds and not crop species (selective herbicides) and the second is to develop crops that are 'tolerant' or 'resistant' to herbicides. The terms 'herbicide tolerance' and 'herbicide resistance' are often used interchangeably.

The options of finding new chemicals and of developing new crop species have both been explored but we will focus on the development of herbicide tolerant crops rather than developments in herbicide chemistry.

Traditional plant breeding

Farmers often select and save seeds for next year's crops from the current crop. By selecting the seeds with desirable traits (often the most productive) crops have been improved from their wild predecessors. Since the 18th Century, plant breeding has been used to identify, reproduce and sell propagating material, usually seeds, to further improve plant varieties. Plant breeders screen for desirable traits in the plants they want to improve or in closely related species. They then hybridize plants (by sexual reproduction) and select the offspring with the desired traits. Undesirable traits may also be transferred with the desired traits and these may need to be selected out in later generations. Three drawbacks of traditional plant breeding are that traits must come from species which can be hybridized or cross-fertilised with the crop plant, that traits other than the desired one are often transferred (Huttner 1997) and that, because of the need to accumulate desired traits and eliminate undesirable traits through several generations of hybridization, the process and rate of genetic improvement are usually slow.

Traditional chemical weed control in crops relies on herbicides that selectively kill certain weeds while having little or no effect on specific crops. One method of increasing the effectiveness of the herbicides is to select specific cultivars of crop plants that are less affected by the herbicides. Plant breeders do select and breed crop varieties with the desirable trait of herbicide resistance. Three main techniques have been used:

- finding herbicide resistant cultivars and crossing them with agronomically desirable cultivars to develop a herbicide resistant, agronomically desirable cultivar;
- selecting within an agronomically desirable cultivar for herbicide resistance; and
- deliberately causing mutations in existing cultivars and then selecting the mutations that provide herbicide tolerance (Faulkner 1982).

Faulkner (1982) used the second technique and selected from whole plants to breed a paraquat tolerant perennial ryegrass and a number of other pasture and grasses resistant to dalapon, paraquat or glyphosate (Johnston and Faulkner 1991). This approach is fairly rare, possibly due to the low priority placed on herbicide resistance by traditional plant breeders and the limited ranges of herbicide resistance levels within crop species (Dyer 1996).

Sebastian *et al.* (1989) chemically mutated soybean seed and selected a line that was tolerant to sulfonylureas by germinating the seeds in the presence of chlorsulfuron. Similar techniques were used by Tonnemaker *et al.* (1992) to produce canola tolerant to sulfonylureas, Fuerst to produce fluazifop tolerant barley and Smith and Newhouse to produce imidazoline tolerant wheat (Dyer 1996). A variation of this technique is to select mutated pollen rather than mutated seeds.

Newer techniques, such as using tissue or plant cell culture to select herbicide tolerant plants, have also been used to produce herbicide tolerant crops. Sugar beet has been selected for tolerance to chlorsulfuron (Hart *et al.* 1992), maize tolerant to imidazolinone herbicides (Anderson and Georgeson 1989) and birdsfoot trefoil tolerant to sulfonylureas have been recovered (Pofelis *et al.* 1992).

Hybridization has also been used in combination with traditional plant breeding techniques to transfer herbicide tolerance to crop plants. Several brassica crops, including Chinese cabbage, canola and rutabaga, have been crossed with the atrazine tolerant weed *Brassica campestris* to produce atrazine tolerant crops (Beversdorf *et al.* 1980). Darmency and Pernes (1989) introduced atrazine tolerance into foxtail millet from the weed green bristle grass and Mallory-Smith *et al.* (1993) introduced sulfonylurea tolerance into domestic lettuce from prickly lettuce.

In Australia, canola varieties with tolerance to two different herbicides have been developed without the use of gene technology. They are Clearfield or ‘imi’ (tolerant to imidazolinone herbicides) and TT (triazine-tolerant) canola. TT canola is estimated to make up half of the Australian canola crop, covering 700,000 hectares (OGTR, 2002b). Herbicide tolerance was transferred to TT canola (from a weedy relative) by classical breeding. ‘Imi’ canola was developed by mutation and selection and it was introduced into Australia in 2000. Two ‘imi’-tolerant wheat varieties were also introduced last year (Grains Research and Development Corporation, personal communication, 2002).

Another method of introducing herbicide tolerance into crops is to use genetic engineering techniques to incorporate genes from organisms such as bacteria that confer tolerance to herbicides into the crop species. The results of this process are transgenic herbicide tolerant crops.

Transgenic herbicide tolerant crops

With the discovery in the 1950s of the genetic code (the mechanism by which living organisms write, store and use the information that defines what they are and how they live) more effective methods of plant breeding have been investigated (Huttner 1997). Now the genes coding for desirable characteristics can be identified, isolated and manipulated. Importantly, the genes can also be introduced into other species. Box 1 describes the methods for inserting foreign genes into plant genomes. These new technologies enable a wider search for desirable genes, not restricted to the crop or closely related species, and make it possible to insert the desired gene without associated unwanted genes.

Herbicide tolerance genes are usually introduced into the nuclear genome, using the methods outlined in Box 1. In 1998, Daniell *et al.* reported a new method of genetically engineering plants using a chloroplast-specific genetic vector. They integrated herbicide tolerance to glyphosate from a petunia gene into the tobacco chloroplast genome. Because chloroplasts are usually inherited maternally and the chloroplast genes are not transmitted by pollen, this type of transformation limits the breeding of the transformed plant and the movement of inserted genes.

Three strategies have been used to generate transgenic herbicide tolerant crops. The first involves altering the site within the plant that the herbicide affects so that it is less sensitive to the herbicide than the plant's native target site. Genes that produce proteins with altered sites for glyphosate and sulfonylurea herbicide action have been isolated and successfully incorporated into crops to produce crops tolerant to these herbicides. The second method is to introduce genes to promote the overproduction of the target site to dilute the toxic effect. This has produced plants weakly tolerant to glyphosate and glufosinate herbicides. The third method is to introduce a detoxification system to inactivate the herbicide before it damages the plant. Tolerance to the herbicides glufosinate, 2,4-D, bromoyxnil and ioxynil has been produced by introducing genes to inactivate herbicides (Huppatz *et al.* 1995). Details of the strategies used to produce tolerance to particular herbicides are in Appendix 2.

Box 1: Introducing foreign genes into plant genomes

There are two main methods of introducing foreign genes into plants; by using bacteria such as the soil organism *Agrobacterium tumefaciens* or by mechanically transferring the gene.

1. The soil bacterium *Agrobacterium tumefaciens* is capable of infecting many plants. When it does, a sequence of DNA (deoxyribonucleic acid) contained in a large plasmid is incorporated into the genome of some of the plant cells. This DNA can be stably incorporated into the host plant genome so that it is inherited normally. In 1983 scientists altered the sequence of the *Agrobacterium tumefaciens* plasmid genes that were inserted into the host plant DNA so that it no longer harmed the plant but was capable of transferring other genes. By selecting cells which had been infected, using a selectable marker in the inserted gene sequence, the transformed cells can be grown into whole plants which contain and can transmit the new genes (Huttner 1997). Because *Agrobacterium tumefaciens* mainly infects dicotyledons, transferring genes into monocotyledons has been more difficult.

2. A number of physical means have been used to introduce foreign DNA into plant cells including: coating beads of gold or tungsten with the DNA and shooting it through the plant cell wall and plasma membrane into the nucleus (particle bombardment); electroporation, where an electric pulse is used to penetrate the cell membrane of cells without a cell wall (protoplasts) and allow the DNA in; using polyethylene gel (PEG) to penetrate the cell membrane of protoplasts; and microinjection, where the DNA is injected under a microscope into the cell nucleus. With all these methods, the cells in which the foreign DNA has been incorporated into the plants' DNA are selected and grown into whole plants (Huttner 1997).

Current transgenic crops

The global estimated area of transgenic crops was 52.6 million hectares in 2001, with an estimated value between US$2.1 and US$2.3 billion in 1999. There were large increases in the area of transgenic crops grown from the mid 1990s but this increase has slowed since 1999 (see Table 1). Over three quarters of this area has been planted to herbicide resistant transgenic crops (see Table 1).

Table 1: Estimated area of transgenic crops

Year	Global area of transgenic crops (million hectares)	Global area of transgenic herbicide tolerant crops* (million hectares)
1996	1.7	0.6
1997	11	7
1998	28	21
1999	40	31.2
2000	44.2	35.9
2001	52.6	40.6

* includes herbicide tolerance in association with other characteristics
Sources: James 1997; 1998; 1999; 2000; 2001

Approximately two thirds of the area planted in 2001 is in the United States of America, with Argentina and Canada contributing another quarter (James 2001). The global transgenic crop production in 2001 is shown in Table 2.

Table 2: Estimated area planted with transgenic crops in 2001

Country	Area (hectares)	Percentage of total
United States of America	35.7 million	68%
Argentina	11.8 million	22%
Canada	3.2 million	6%
China	1.5 million	3%
Australia	0.2 million	<1%
South Africa	0.1 million	<1%
Mexico	<0.1 million	<1%
Bulgaria	<0.1 million	<1%
Uruguay	<0.1 million	<1%
Romania	<0.1 million	<1%
Spain	<0.1 million	<1%
Indonesia	<0.1 million	<1%
Germany	<0.1 million	<1%
Total	52.6 million	100 %

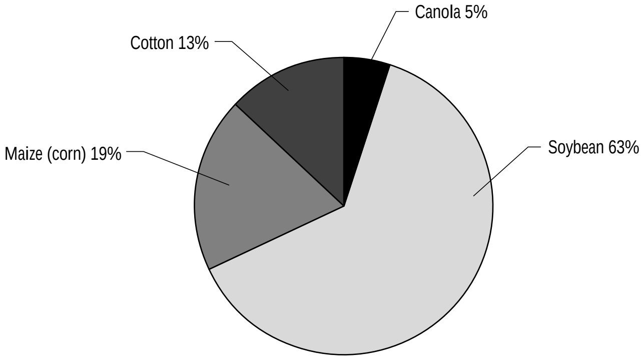
Source: James 2001

The United States of America is the main grower of transgenic crops and its share of the global crop has varied from 51% (1996) to 74% (1997 and 1998) (James 1998, 1999, 2000). By the end of 1998, 56 transgenic crop products had been approved for commercialisation in at least one country. The crops consisted of 13 different crops and six traits. Intellectual property rights were owned by 22 organisations, 19 private corporations and 3 public sector organisations (James 1998). According to Agriculture and Biotechnology Strategies (Canada) Inc (2001), 75 GM crops have now been approved for commercial use in at least one country.

This list is not exact because it includes some products awaiting final approval, for example, transgenic melons in the US. The list also includes approvals for use, rather than growing, for example, herbicide tolerant canola is listed as approved in Australia. Its use in foods has been approved by Australia New Zealand Food Authority (the predecessor of Food Standards Australia New Zealand) but commercial cultivation has not yet been approved. Two applications for commercialisation of herbicide tolerant canola were received by OGTR earlier this year.

In 2001 the main transgenic crops were soybean, maize (corn), cotton, and canola. Figure 3 shows proportion of the 2001 global transgenic area planted with each crop. Of the 52.6 million hectares of transgenic crops grown in 2001, 40.6 million hectares consisted of herbicide tolerant soybean, corn and cotton, 7.8 million hectares were planted with insect resistant crops and 4.2 million hectares were planted with both herbicide and insect tolerant GM cotton and maize (James, 2001).

Figure 3: Percentage of the area of the global transgenic crop, by crop, in 2001.



Source: James 2001

Transgenic crops are now important to American agriculture. In 2000 in the United States of America, 61 per cent of the cotton crop, 54 per cent of the soybean crop and 25 per cent of the maize crop was transgenic (United States Department of Agriculture 2000). Transgenic herbicide tolerant canola was estimated at 62 per cent of the Canadian crop in 1999 (James 1999).

Commercial transgenic crops in Australia in 2000 were up to 180,000 hectares of transgenic insect resistant (*Bt*) cotton and small areas of carnations modified for violet colour or increased vase life (Australian Broadcasting Commission 2000; Genetic Manipulation Advisory Committee 1998). The carnations are also tolerant to sulfonylurea herbicides.

Future transgenic crops

Between 1986 and 1997 about 25,000 field trials were conducted on more than 60 transgenic crops with 10 traits in 45 countries. Trials conducted in the United States of America and Canada accounted for more than 70 per cent of the total, followed by Europe, Latin America, Asia and South Africa. Trials were most common for maize, tomato, soybean, canola, potato and cotton and the most frequent traits considered were herbicide tolerance, insect resistance, product quality and virus resistance (James 1997).

Transgenic herbicide tolerant crops were the most common category of transgenic crops trialed in 1986 to 1992 (40 per cent) and remain so today (42 per cent) (Organisation for Economic Co-operation and Development 1993a; Foster 2001).

In the United States of America, 53 different transgenic plants have been assessed by the Animal and Plant Health Inspection Service (2001) and are approved for commercial use. Thirty two of these are herbicide tolerant. The crops are canola, chicory, cotton, flax, maize, potato, rice, soybean and sugar beet. The herbicides the crops are tolerant to are: phosphinothricin or glufosinate ammonium (18 crops), glyphosate (10 crops), bromoxynil (two crops) and sulfonylurea (two crops).

Transgenic herbicide tolerant crop varieties in Australia

The crops for which herbicide tolerant varieties have been assessed for Australian field trials are listed in Table 3. The transgenic crops which have been approved for general release in Australia are two types of transgenic carnations, one modified for violet colour and the other for increased vase life, insect resistant cotton (*Bt* or INGARD®), herbicide tolerant cotton (Roundup Ready®) and both herbicide tolerant and insect resistant cotton (Roundup Ready®/INGARD®).

Table 3: Commercial releases and field trials of herbicide tolerant crops in Australia (assessed to October 2002)

Crop	Number of trials	Number of extensions to trials	Number of general releases
Cotton	17	34	2
Canola	10	23	
Field peas	9	2	
Lupins	5	3	
Carnations	3	1	2
Wheat	3	1	
Barley	3	1	
Subterranean clover	2	3	
Roses	1		
Indian mustard	1	3	
Pineapples	1		
Poppies	1		
Lentils	1		
Tomatoes	1		

Source: Genetic Manipulation Advisory Committee 2000, Interim Office of the Gene Technology Regulator 2000a; 2000b; 2001a; 2001b., Office of the Gene Technology Regulator 2002a

The Regulator is currently considering an application for commercial release of herbicide tolerant GM canola. A decision in relation to this application is expected in early 2003.

3. Benefits of transgenic herbicide tolerant crops

Herbicide tolerant crops are being developed to improve the productivity and sustainability of farming systems by improving weed control. According to McLean and Evans (1997), the potential benefits include:

- reduced injury to crops
- effective control of difficult weeds
- more efficient use of farm inputs such as fuel and labour
- overall reductions in herbicide use
- increased options for weed control
- slowing the emergence of herbicide resistant weeds
- reducing damage to soil from tillage
- improved rotational options through a reduction in residual herbicides
- increased flexibility of farming options
- and a reduction in adverse environmental impacts of herbicides.

These points focus on benefits to agriculture and can be classified into improved weed control, increased management options and environmental benefits.

The community can also benefit from herbicide tolerant crops. Biotechnology, seed and chemical companies involved in developing and selling herbicide tolerant crops and complementary herbicides will benefit from the use of the crops. Consumers and the wider community can also benefit from increased farm productivity and sustainability (Duke 1995) and improvements to the environment. Also, each yield improvement to existing agricultural land potentially means that less biodiversity-rich land, such as rainforest, needs to be brought into agriculture (House of Lords 1998).

Improved weed control

The main purpose of developing herbicide tolerant crops is to control weeds. Because weeds compete with crops for resources such as nutrients, light and water, effective weed control can increase crop yields (Conner and Field 1995). These yield increases should increase or maintain farmers' profits and sustainability (Duke 1995) and have wider community benefits.

Herbicide tolerant crops can also reduce the damage to crops that weeds or weed control measures cause. Crops can be devalued by contamination; for example, the acceptability of canola for human and/or animal consumption can be undermined by contamination with seeds from other plants. Improved weed control provided by herbicide tolerant canola could reduce contamination and increase the value of the crop. Crop damage can also be caused by spraying nearby crops with herbicides -if the crop was tolerant to the herbicide, the damage would be less.

A number of agricultural weeds are difficult to control. Parasitic weeds in Africa, such as witchweed or dodder, are examples. The crops and weeds could be sprayed with herbicide if the crop plants were tolerant to the herbicide (Duke 1995). It may also be possible, and cheaper, to control these weeds by applying herbicide to herbicide tolerant seeds before planting (J. Gressel, Weizman Institute of Sciences, Israel, personal communication).

There are also weed problems in Australia that herbicide tolerant crops could assist in solving. In Western Australian cropping systems, lupins are grown in short rotations with winter cereals and ryegrass is a common weed that has developed resistance to a number of herbicides (see Appendix 3). The ryegrass may be able to be controlled if lupins tolerant to a non-selective herbicide such as glyphosate were grown and the herbicide applied while the lupins were growing (McLean and Evans 1997). However, glyphosate resistant ryegrass has been discovered in New South Wales and Victoria (Heap 2001) and Western Australia (Australian Broadcasting Corporation 2001) and careful management would be needed to avoid allowing glyphosate resistant ryegrass problems to develop in the Western Australian agricultural environment.

Increased management options

While improving yield through effective weed control is one advantage from using herbicide tolerant crops, US farmers have found the crops provide greater management advantages (Carpenter 2001b). Farmers can use fewer types of chemicals, for example, only using glyphosate herbicide, instead of using a range of herbicides as mixtures or during different stages of the growing cycle. This makes managing the farm more efficient. Further efficiencies occur due to reduced cultivation under minimum tillage systems. In Canada, reductions in tillage led to fuel savings of 5-6 litres per acre and aided in soil conservation (Canola Council of Canada, 2001b). Fuel and labour costs are also decreased by the reduction in herbicide applications (Romahn 1998).

Herbicide tolerant crops should enable greater flexibility in timing operations to adjust to variable climatic conditions, particularly with Australia's highly variable rainfall. If herbicide tolerant crops are planted, weeds can be sprayed after sowing. This means that when rainfall is favourable, farmers could plant immediately and spray later rather than having to spray out the weeds before planting a crop. This would enable farmers to respond rapidly to seasonal conditions.

Herbicide tolerant crops can also increase the area available to cropping by enabling crops to be grown in areas with difficult weed problems or contaminated with residual herbicides. They can also enable more flexibility in crop rotations, particularly if the herbicides used are active for more than a single rotation.

When crops are sown as mixtures, such as mixed pastures of grass and clover, herbicide options are limited by having to use herbicides both species can tolerate. Introducing herbicide tolerant crops increases the number of herbicides that could be used (Conner and Field 1995). Some crops benefit from high plant densities during early growth phases but need to be thinned out later. Mixing herbicide tolerant seeds with susceptible seeds would avoid expensive mechanical thinning of the crop in favour of chemical thinning (Conner and Field 1995).

Another potential agronomic use of herbicide tolerance is in seed production. Using herbicide tolerance in the valuable crop and treating with herbicide could reduce contaminating seeds in pure seed production. Herbicide tolerance, in association with male sterility, can also increase the efficiency of hybrid seed production (Conner and Field 1995). Herbicide tolerance in minor crops such as lettuce could encourage the registration of herbicides for those crops, a practice not currently popular with herbicide manufacturers but likely to assist weed management in minor crops (Duke 1995).

Herbicide tolerant crops are expected to increase the life of the existing chemical herbicides and they provide more options for weed control, which may slow the emergence of herbicide resistant weeds. However, applying a number of herbicides in succession could also increase selection pressure for multiple resistant weeds (Duke 1995).

Environmental benefits

There are also a number of potential environmental benefits from using herbicide tolerant crops. Firstly, the herbicides that complement the herbicide tolerant crops are the newer ones, which are thought to be less damaging to the environment. They are considered to have better agronomical, toxicological and environmental characteristics. Also, the aim of developing herbicide tolerant crops is to reduce the total amount of herbicides used by making herbicide application better targeted. By using herbicide tolerant crops, farmers will be able to wait until after planting to apply herbicides, the amount and type being dictated by the known weed infestation. Larger prophylactic doses of soil-incorporated or soil-applied herbicides could be avoided (Duke 1995). Lower herbicide application rates and the use of less damaging herbicides will reduce herbicide residues in the environment, including soil and water. Targeted applications of the newer herbicides, which are active when applied to foliage, could also reduce the movement of herbicides and their metabolites to surface and ground waters (Duke 1995). A change to less damaging herbicides and fewer applications of them will also reduce occupational health and safety risks to farm workers and others by reducing chemical exposure.

It is argued that it is more environmentally sustainable to use herbicides to control weeds rather than cultivation, especially in Australia where soil textures are fragile and minimum tillage methods have been developed to decrease soil erosion (Hamblin 1987). Disturbing the surface of the soil leads to a reduction in organic matter and in the numbers of micro-organisms, increases moisture loss and exposes the land to wind and water erosion, with serious long-term consequences for the environment. In Australia, soil erosion is very important since the shallow topsoils have suffered considerably from excessive cultivation, the burning of stubble and the clearing of marginal land. In some areas the loss of topsoil through wind erosion has been so severe that farming practices were forced to change to wider rotations to increase organic levels in the soil (Millis 1995). No-till systems can also reduce the loss of soil carbon to the air as carbon dioxide, thereby potentially reducing atmospheric warming (Roush 2001). Herbicide tolerant crops could increase opportunities for implementing minimum tillage farming practices and decrease soil erosion and soil carbon loss.

Environmental benefits from planting herbicide tolerant crops may extend to insects and soil micro-organisms. As weeds could be allowed to grow for longer, bare earth surrounding crops will be replaced by a mulch of dead and dying weeds, which would be preferred by insects and soil micro-organisms. The mulch may also encourage insects away from the crop on to the weeds (House of Lords 1998).

The prospect of increased profitability due to better weed control, simplified management practices and environmental benefits probably appeals to both farmers and the wider community but raises the question ‘At what cost?’ The risks of the technology are examined in the next chapter.

4. Risks of transgenic herbicide tolerant crops

While transgenic herbicide tolerant crops have the potential to increase the productivity and sustainability of farming systems, they also carry potential risks. The risks which have been raised about transgenic herbicide tolerant crops include:

- herbicide tolerance transferring to weeds, rendering the herbicide useless in the longer term
- the crops being less nutritious or producing toxins, allergens or carcinogens
- the crops being more susceptible to disease or more demanding for soil nutrients
- the crops having undesirable agronomic characteristics such as lower yields, greater susceptibility to disease or otherwise being uneconomic
- the crops increasing the use of herbicides; and the use of the technology concentrating commercial power over the seeds, herbicides and fertilisers (Millis 1995).

Other risks from herbicide tolerant crops, listed by Bowes (1997), include:

- herbicide resistant weeds becoming more invasive and difficult to manage
- greater herbicide residues (and metabolites) in food produced from herbicide tolerant crops
- transgenic crops altering the microbial balance of soils
- bacteria in humans and animals being affected by exposure to foods containing antibiotic resistance marker genes
- and transgenic crops resulting in a loss of biodiversity of the world's plant species.

Risks which may arise over a longer time frame include:

- slower development of the next generation of herbicides
- decreasing the genetic diversity of crop species
- adverse effects on biological diversity, for example on-farm conservation
- loss of existing domestic and international markets
- reduced competitiveness of Australian agriculture
- and enabling agriculture to proceed beyond sustainable limits.

Some of these risks are new and exist only for transgenic herbicide tolerant crops. Others exist with herbicide tolerant crops developed by all methods, including traditional breeding, while some are historical agricultural risks and apply equally to all new crops. Some of the risks are associated with qualities of the crop, such as the introduction of toxic compounds from the genetic alteration, while others depend on the ecological system the crop inhabits. The risks can broadly be categorised into risks to human health and safety; risk of increasing weed problems; and other risks, including commercial risks to growers and to agricultural sustainability.

Health risks

Concerns about possible adverse effects on people from using transgenic crops to produce food have been raised. The concerns are based around the safety of the food itself; changed patterns of herbicide or pesticide use on food crops; the possibility of increasing antibiotic resistance problems from the antibiotic resistance markers used in many of the transgenic crops and a lack of knowledge about long-term effects of genetically modified foods in the diet.

Food safety

To assess the safety of foods derived from transgenic crops, Food Standards Australia New Zealand, the Organisation for Economic Co-operation and Development, the World Health Organization and the Food and Agriculture Organisation of the United Nations have adopted the concept of 'substantial equivalence' (Organisation for Economic Co-operation and Development 1993b; World Health Organization 1993). This concept enables safety assessments to start by comparing data about the molecular structure, composition and nutritional value of a transgenic food with data from a traditional food with a history of safe food use (World Health Organization 2000). The differences between the new food and the traditional food are identified and become the focus of safety assessments. If no safety issues arise, 'substantial equivalence' is established and the product is considered as safe as the traditional food. Where a potential problem is identified, additional studies may be required to assess the risks (Australia New Zealand Food Authority 2000a). In most countries, including Australia, foods derived from genetically modified plants that are not 'substantially equivalent' are required to be labelled so that consumers know the difference between the genetically modified food and its conventional counterpart.

The idea of substantial equivalence has been subject to a lot of criticism from various sectors, particularly those people opposed to the use of gene technology in food. They tend to believe that foods derived from biotechnology are, by definition, not equivalent to conventional foods. The concept of substantial equivalence has recently been reviewed and it is seen as a powerful tool for identifying differences between new foods and their conventional counterparts and subjecting those differences to analysis (World Health Organization 2000).

Genetically modified foods may be required to be tested in animal feeding studies before approval can be given for their use. More than 40 animal feeding studies, designed to detect any unintended effects in livestock fed transgenic crops, have been completed or are currently in progress. Many of these studies, conducted in Europe and the US, compared the performance of livestock fed either transgenic or non-transgenic feeds and have included dairy cows, beef cows and feeders, broilers, layers, swine, sheep and catfish. The transgenic crops studied were pest protected corn and herbicide tolerant soybeans, corn and sugar beets. Conclusions for these studies have been very consistent—no detrimental effects have been found in livestock fed transgenic crops (Faust 2001). Clark and Ipharraguerre (2001) reviewed the results from 23 animal feeding experiments conducted over the past four years at universities throughout the United States of America, Germany and France. In each study, separate groups of chickens, dairy cows, beef cattle or sheep were fed either transgenic or conventional corn or soybeans as a portion of their diet. Each experiment independently confirmed that there is no significant difference in the animals' ability to digest the transgenic crops and no significant difference in the weight gain, milk production, milk composition and overall health of the animals when compared to animals fed conventional crops. In these experiments, the transgenic corn was either insect resistant or tolerant to the herbicide glyphosate and the soybeans were tolerant to the herbicide glyphosate. Separate studies showed that there was no significant difference in the nutritional composition of the grains themselves.

There is a well-known case where animal feed trials have been used to suggest that transgenic foods are inherently unsafe. This was in 1998 when Dr Arpad Pusztai claimed during a UK television interview that rats were harmed by being fed transgenic potatoes. This led to considerable public and scientific debate about his experiments. When his experiments were reviewed by the Royal Society and The Lancet, the research was found to be poorly designed and executed and there was no evidence that genetic modification made food unsafe (see Box 2).

Particular issues that have been raised about transgenic crops are that they could introduce toxins, allergens or carcinogens into people's diets or alter the amount of nutrients or anti-nutrients such as lectins or neurotoxins or change the availability of nutrients in the diet.

Many plants, including common foods such as potatoes, produce toxins. Care needs to be taken that genetic manipulation of crops does not increase the production or concentration of naturally occurring toxins in food, introduce new toxins or introduce toxins into different foods where people may not expect the toxin and may not prepare food appropriately. In the past, traditionally bred potato cultivars have been withdrawn due to excessive levels of toxic glycoalkaloids in the potatoes (Zitnak and Johnston 1970; Hellenäs *et al.* 1995). Other examples are a conventionally bred squash with excessive levels of curcurbitacin and a variety of celery containing excessive levels of psoralen (Jonas 2000). Examination of potential toxic effects takes place during safety assessments, where any differences between the transgenic food and traditional food are examined closely.

Box 2: Pusztai and genetically modified potatoes

In 1998, Dr Arpad Pusztai claimed during a television interview that rats were being harmed by being fed transgenic potatoes. He said his experiments showed that feeding rats transgenic potatoes had a significant effect on the rats and he concluded that transgenic foods could have adverse effects on humans. Pusztai published his research results on the Internet (Pusztai 1998).

Pusztai fed the rats a diet of transgenic potatoes that he admitted in the research contained protein levels that were too low to adequately sustain the rats. To compensate for this he added protein to their feed in varying amounts. When the rats were measured, differences were found between the rats fed the transgenic potatoes and those fed the traditional potatoes. The differences involved effects on organ development, body metabolism and immune function.

The UK Royal Society criticised the research as ‘flawed in many aspects of design, execution and analysis and that no conclusions should be drawn from it’ (Murray *et al.* 1999). The Lancet published Pusztai’s research (Ewen and Pusztai 1999) and critiques of the research. One commentator claimed ‘A physiological response of this nature is probably of little significance’ because the results were consistent with ‘short-term feeding of various poorly digestible carbohydrates’ (Kuiper *et al.* 1999).

Similar care needs to be taken to ensure allergenic substances are not introduced by genetic modification of food. True food allergies involve abnormal immunological reactions to substances, usually naturally occurring proteins, in foods (Mekori 1996). In allergic people the allergen causes an immunological response with a range of possible symptoms, including hives, eczema, asthma, anaphylactic shock, nausea and vomiting. A protocol to test the allergenicity of foods derived from transgenic food crops has been established (Metcalfe *et al.* 1996) that involves considering the source of the gene, similarity to known allergens, reactions of the new protein with serum from people known to have allergies to the protein source and the physico-chemical properties of the new protein. (Most allergens are between 10,000 and 40,000 molecular weight and resistant to acid and protease degradation.) The protocol was used to test a transgenic soybean containing a high methionine storage gene from Brazil nuts, designed as an improved animal feed. The transferred protein was found to be an allergen and commercial interest in the soybean ceased (Nordlee *et al.* 1996). The protocol has since been updated twice (World Health Organization 2000, Food and Agriculture Organization 2001), with a recommendation that it be kept under review as scientific knowledge in the fields of allergenicity and biotechnology are rapidly expanding.

It is not as easy to test for carcinogenic compounds as it is for toxic and allergenic compounds in food because toxic and allergic reactions are fairly immediate but cancers usually take longer to develop. A similar protocol based on analysing any new proteins, their known activity and comparisons with known carcinogens, along with testing, will provide a good indication of potential safety issues. Animal feeding studies, discussed above, compare the nutritional characteristics of transgenic crops with those of conventional crops.

Herbicide or pesticide residues

The use of transgenic crops may alter the way agricultural chemicals such as herbicides and pesticides are used. While the majority of transgenic crops have been developed to reduce the use of the chemicals (insect resistant crops) or to complement the safer herbicides, changed patterns of use may affect food safety. Herbicides and their metabolites could be found in different places in the food chain. These issues are assessed before approval is given to alter the way chemicals are used on crops, for example, by the National Registration Authority (NRA) in Australia and the Environmental Protection Authority (EPA) and United States Department of Agriculture (USDA) in the United States of America.

Antibiotic resistance markers

Many transgenic plants use antibiotic resistance genes as markers to select for the rare recombinant plants during development. Concern has been expressed about the risk of these genes transferring to pathogenic micro-organisms in the human and animal gut and adding to antibiotic resistance problems in human medicine, such as vancomycin resistant enterococci (Australia New Zealand Food Authority 2000a).

For genes to be transferred to bacteria in the gut, a series of extremely improbable steps would have to occur. Firstly, the gene would have to be released in a single piece from the genetically modified plant cells. Many food preparations we use daily, including processing and cooking, break up the genetic material in the food we eat. Secondly, the gene would need to survive intact after digestion by the enzymes in the gut, including the ribonucleases, which break genetic material into short chains. Next, the entire gene would have to be taken up by a bacterium in the gut.

The likelihood of genetic material being taken up by bacteria in the gut has been considered by scientists around the world. They have concluded that the probability that any genetic material being taken up is extremely low and that the probability for an intact antibiotic resistance gene to be transferred is even lower (World Health Organization 1993; Lachmann 1998). Attempts to show such transfers can happen are being made, with Nielsen *et al.* (2000) demonstrating that a soil bacterium *Acinetobacter* can be made to take up DNA in the laboratory and Gebhard and Smalla (1998) showing that *Acinetobacter* can take up DNA from transgenic sugar beet. Mercer *et al.* (1999) showed that lengths of DNA can be taken up by bacteria which are normally present in the mouth. All of these studies were conducted under optimised laboratory conditions and not under field conditions (Beever and Kemp 2000).

If antibiotic resistance were to successfully transfer from a transgenic plant to a bacterium, the gene would have to survive the bacterium's natural defences and stably integrate into the bacterium's genome. The antibiotic resistance gene would soon be lost if it was not incorporated into the bacterium stably, so that it could be passed on to the next generations of bacteria. The gene would then need to be expressed correctly so that the protein that protects against the antibiotic is produced. If the bacterium does not produce the protein, the bacterium would be susceptible to the antibiotic. The antibiotic resistance gene would also need to survive many multiplications of the bacteria. Antibiotic resistance genes are only likely to survive over many generations in bacteria if the bacteria are regularly exposed to the antibiotic in question (Australia New Zealand Food Authority 2000a; Salyers 1997).

The probability of such an event happening is therefore considered very remote. For example, the United Kingdom House of Lords Select Committee on European Communities (1998) found that the ‘Transfer [of genes] from plants to bacteria is extremely improbable’. The World Health Organization (1993) also considered the risks of antibiotic resistance genes transferring were negligible and a recent review endorsed this conclusion (World Health Organization 2000). The extremely small possibility of gene transfer from genetically manipulated plants must be considered with the well-known main culprits for antibiotic resistant pathogens; the abuse and overuse of antibiotics in people and animals (Pittard 1997).

Even though the probability of antibiotic gene transfer is considered remote, alternatives are available with herbicide tolerant crops and other options are being developed. Herbicide tolerant crops can use the trait of herbicide tolerance as a marker. Various lines of canola, carnations, corn, cotton, rice and soybeans are approved for commercial use around the globe that use this feature to avoid antibiotic resistance genes.

Using herbicide tolerance as the only selectable marker is not always desirable and new methods for removing antibiotic resistance genes are being established. It is now possible to remove the antibiotic resistance marker genes once they have been used in the initial identification of transgenic plants (for example, Iamtham and Day (2000) removed antibiotic resistance markers from tobacco chloroplast genes). Trials are now being conducted of alternative markers to antibiotic resistance genes but none are being used in plants approved for release yet.

The European Union recently introduced a deadline for the gradual elimination of antibiotic resistant markers in transgenic organisms, of 2004 for commercial releases and 2008 for research (Morris 2001). The specific antibiotic resistance gene that is used as a marker is also considered by authorities, such as the OGTR in Australia. Consideration is given to how widespread resistance genes to that particular antibiotic are in the environment and how important the antibiotic is in treating animal or human diseases. Only those markers that are considered not to increase the incidence of antibiotic resistance are approved. For example, kanamycin is the most common antibiotic resistance marker and is not used for treating human diseases in Australia.

Transfer of genes from GM food to animals and people

One concern that is raised about food from transgenic crops is that these crops contain genes that could be passed on to people or animals who eat the crops and that these genes will harm people. This is often based on a misconception that only transgenic foods contain genes and not an understanding that cells of all living organisms, including the plants and animals we eat, contain genes.

A number of studies have been conducted in Europe and the US to evaluate milk, meat, eggs, and other tissues from dairy cattle, beef cattle, broilers, and layers fed transgenic and non-transgenic crops (for example, Faust 2001; Faust and Miller 1997; Klotz and Einspanier 1998; Novartis Seeds 1999; Einspanier *et al.* 2001; Doerfler 2000). Two of the studies reported finding small fragments of a naturally occurring (non-transgenic) plant chloroplast gene in animal tissues such as lymphocytes and leucocytes (Faust 2000). However, in all the studies, no transgenic DNA was found in the animals or animal products. Results from other studies indicated no plant source DNA (naturally occurring or transgenic) was detected in meat, milk, eggs or other tissues such as spleen (Faust 2000). Results from all these studies agree on two points – no transgenic DNA and no transgenic proteins have been detected in meat, milk and eggs (Faust 2001). These results are not surprising if we consider that the vast majority of DNA we consume when eating transgenic crops is from conventional plant material and not from the genetic modification, with estimates of less than seven millionths being due to the genetic modification (Beever and Kemp 2000).

For millions of years animals and people have been exposed to genes in the food they eat and there is no evidence that any plant proteins are expressed in tissues of any animals that have eaten plants. Also, no plant gene (or plant gene fragment) has ever been detected in the human genome or that of any other animal (Beever and Kemp 2000). This indicates that humans and animals have developed methods for preventing the incorporation of foreign DNA into their genomes.

Long term effects

There is a possible indirect effect from the use of transgenic foods on diet and nutrition. Altered food availability and consumption patterns could have long term health effects, both adverse and beneficial, not directly due to the technology but as an indirect result of changes in the food supply (House of Lords 1998).

There is no reason to suspect that the long-term safety of transgenic foods will be any less than that of conventional foods. The safety assessment Food Standards Australia New Zealand (FSANZ) conducts on the foods is designed to ensure that transgenic foods provide all the benefits of conventionally produced foods and no additional risks (Australia New Zealand Food Authority 2000a). Nevertheless, FSANZ is monitoring a feasibility study initiated by the UK Food Standards Agency to see if it is possible to track the buying patterns of tens of thousands of consumers and link the consumption of transgenic food with health (Biotechnology Australia 2000).

Weed risks

The main risk to the environment proposed as arising from the use of herbicide tolerant crops is that weed problems will emerge or increase, particularly herbicide resistant weed problems. There are three mechanisms by which herbicide resistant weeds could emerge. Firstly, the crop itself could become a weed in subsequent crops or pastures (volunteer weeds); secondly, herbicide tolerance genes could spread to weedy species (introgression); or thirdly, repeated applications of herbicides could encourage the selection of weed populations resistant to that herbicide.

Volunteer weeds

Few crops are fully harvested and the remaining propagules (parts of the plant that can develop into a new plant) can become volunteer weeds in following seasons. If a significant number of propagules survive the off-season (winter in temperate climates and the dry season in many tropical climates) they are capable of causing a problem. The volunteer plants become weeds when they affect the productivity of subsequent crops or are found in other places where they are unwelcome. For example, potatoes can infest many subsequent crops as a competitive weed, both as tubers and long-lived seeds (Love 1994). These volunteer potatoes can also affect rotational systems established to prevent the carryover of soil borne potato diseases. Canola seeds can also persist for many years in the soil seed bank and their progeny can appear in following crops (Lutman 1993), particularly if harvest conditions are poor, when up to 7 per cent of canola can spread its seed (Price *et al.* 1996). Undesirable canola cultivars can decrease the value of following crops, including subsequent canola crops.

In some cases transgenic herbicide tolerant crops can help solve a volunteer weed problem by allowing control of the volunteer weeds in the next, herbicide tolerant, crop. For example, low value conventional canola seeds from the previous year will be affected if a glyphosate tolerant canola crop is sprayed with glyphosate. Rotating herbicide tolerances as well as crops could help volunteer weed control in agricultural systems, although crops with two or more herbicide tolerant traits may require special management (Thill 1996).

Crop plants can also spread to become volunteer weeds on road and rail verges and other non-intended sites. For volunteer weeds outside cropping sites, does the problem change if the weeds are herbicide tolerant? If herbicides are not used on the weeds, herbicide tolerance in itself would not provide a competitive advantage and the consequences of the weeds being herbicide tolerant are likely to be minimal. In other situations, herbicides may be used to control volunteer weeds, for example, herbicide can be sprayed to form fire breaks on road and rail verges. In these situations, tolerance to the herbicide used could make weed control and the fire breaks less effective. Herbicide tolerance in volunteer weeds could also limit control options in other areas if control became necessary; for example, if volunteer weeds became a problem in a conservation area.

Volunteer weeds are not a problem unique to the introduction of transgenic herbicide tolerant crops, they can also occur when conventionally bred herbicide tolerant crops such as triazine tolerant canola are grown. This does not diminish the need to consider the risk from herbicide tolerant volunteer weeds when assessing transgenic herbicide tolerant crops.

Introgression

‘The greatest perceived risk (from herbicide resistant crops) is the potential for transfer of herbicide resistance from transgenic crop varieties to their weedy relatives, whether they be related weedy species or weedy races of the crop species’ (Sindel 1997). Two mechanisms for gene transfer (introgression) are thought to be possible. The first is within species or between closely related species through outcrossing (hybridisation with related plant species) and the second is for the transfer between totally unrelated species through horizontal gene transfer (Rissler and Mellon 1993).

Outcrossing

Hybrid plants are the result of crossing of two plant varieties, races or species. The progeny contain genetic material from both parents, which could include herbicide tolerance genes from one of the parents. Five conditions need to be met for hybrids to form:

1. The two species must be sexually compatible and capable of producing hybrid progeny;
2. The crop and weed species have to flower at the same time
3. A vector needs to be available to carry pollen from the crop to the weed (the vector could be an insect, the wind or agricultural machinery)
4. The two species need to be physically close enough for the vector to disseminate the pollen
5. The environment must permit cross pollination and the production and survival of hybrid plants (Dale and Irwin 1995).

There are many examples of weed species hybridising with crop species. Apart from the simple gene transfer by cross pollination from crops to their wild relatives belonging to the same species, closely related species may have compatibility barriers which can occasionally be surmounted. Examples of genetic exchange between crop species and weeds, include rice and perennial rice; maize (corn) and teosinte; sugar beet and wild beet (Dale 1994); oats and wild oats; sorghum and Johnsongrass (Thill 1996); rye and its wild relatives (Jain 1977); and the squash family and Texas gourd (Decker and Wilson 1987). Canola (*Brassica napus*) has been found capable of forming spontaneous hybrids with many wild relatives including *Brassica rapa*, Chinese mustard, black mustard, Greek mustard and wild radish (Scheffler and Dale 1994).

To assess the risk of a herbicide tolerant crop crossing with weedy relatives, the presence or absence of relatives of the herbicide tolerant crop in the surrounding environment first needs to be established. For interbreeding to occur in the field, the flowering times of the plants must overlap at least partially. Flowering times can vary with the seasons and the potential for the flowering times to overlap because of unusual environmental conditions needs to be considered (Gressel and Rotteveel 2000).

The next consideration is if the pollen can carry from the crop to the weedy relative. The distances pollen can travel have been reported for many crops and are used for the production of pure seeds. They range from 18 metres up to 3000 metres (Thill 1996, Rieger et.al. 2002). The spread of pollen from transgenic crops has been measured during field trials (for example, McPartlan and Dale [1994] measured pollen spread from potatoes and Scheffler *et al.* [1993] measured spread from canola). While these trials provide valuable information, it has been found that data from small-scale trials may be of limited help in determining the potential for pollen to spread from large field trials or released transgenic crops (Department of the Environment, Transport and the Regions 1999). While the movement of pollen is measurable, it also needs to be considered that volunteer weeds from the transgenic crop may persist and spread in the environment, flower at different times and cause pollen to spread further than expected (Gressel and Rotteveel 2000).

It has been found that genes will spread from crops to wild relatives. Wolfenbarger and Phifer (2000) found natural hybridisation occurs between 12 of the world's 13 major crop species and wild relatives (including wheat, rice, maize, soybean, barley and cotton) and for seven of the 13 (wheat, rice, soybean, sorghum, millet, beans and sunflower), hybridisation with a wild relative has contributed to the evolution of some weed species (Ellstrand *et al.*1999). For example, Johnsongrass is an economically important weed that has gained fitness advantages by gene flow from cultivated sorghum (Keeler *et al.*1996). This shows that introduced genes will spread, albeit rarely.

The third consideration in assessing the risk is whether the introduced genes survive in wild plant populations. It has been thought that hybrids between crops and weeds would not survive because the traits considered desirable in crops, such as dwarfing and non-shattering seeds, would make the hybrids at a competitive disadvantage to weeds without these traits (National Research Council 1989). Some cases of hybrids persisting have proven this is not always true. Persistent hybrids have been found between sorghum and Johnsongrass; cultivated and wild radishes; and rice and wild rice (Arriola 1999). Mikkelsen *et al.* (1996) found hybrids of herbicide tolerant canola (*Brassica rapa*) crossed with weedy *Brassica campestris* were herbicide tolerant and, when crossed with *Brassica campestris,* showed no significant decrease in fitness. This provides evidence that introduced genes can persist in wild populations but gives no indication of what the consequences of the spread could be.

Whether a herbicide tolerant gene transferring from a crop to another species increases weed problems depends on the gene, the herbicide use patterns and on the alternative management strategies available (Gressel and Rotteveel 2000). The effect of the spread of herbicide tolerance in an ecological system will depend on how well adapted the crop is to the particular climate, soil conditions, and so on, of individual sites (Organisation for Economic Co-operation and Development 1997). It will also depend on and vary between the environments the plants grow in and can spread to. Herbicide tolerance spreading to an existing ruderal species (one found on waste ground or rubbish heaps) that is never controlled may not cause a problem but the effect could be vastly different if herbicide tolerance is introduced to an existing weed that then spreads through a farmer's fields. This could increase weed management problems for farmers.

In summary, herbicide tolerance genes are capable of transferring from crops to wild relatives and, in some situations, these genes will survive in the environment. The effect of the spread of herbicide tolerance genes will depend on the particular environment, the gene, the current weed management strategies and possible alternatives. This issue is discussed in more detail in a recent Bureau of Rural Sciences report (Glover, 2002).

Special problems may arise when herbicide tolerance genes transfer into crops with an existing, different herbicide tolerance, for example, if a glyphosate tolerance gene from canola transferred into a glyphosate sensitive but triazine tolerant canola crop. There are currently being marketed, or are under development, canola with tolerance to six herbicides: triazines, glufosinate, glyphosate, imidazolines, 2,4-D and bromoxynil (Co-operative Research Centre for Weed Management Systems and Avcare 1998). There may also be cases where multiple tolerances are deliberately introduced into a crop species, such as a combination of a grass herbicide tolerance with a broadleaf herbicide tolerance to solve a specific agronomic need. The multiple tolerant crops will require careful management (Co-operative Research Centre for Weed Management Systems and Avcare 1998).

Horizontal gene transfer

Since genes, including herbicide tolerant genes, are often introduced into crops by a plasmid from naturally occurring bacteria such as *Agrobacterium tumefaciens* (see Box 1), the possibility of the same mechanism transferring genes between unrelated species in the natural environment has been raised (Rissler and Mellon 1993). This is an example of horizontal gene transfer, which is the movement of genetic material between individuals independently of normal reproductive mechanisms. Nielsen *et al.* (1998) reviewed information on the transfer of genes from plants to soil and plant associated bacteria, including *Agrobacterium* species. Field and laboratory experiments were not able to confirm horizontal gene transfer from plants to naturally occurring bacteria, although laboratory studies (Nielsen *et al.* 1997; Gebhard and Smalla 1998) succeeded in transferring specially designed genes from plants to bacteria. From the few examples available, the frequency of gene transfer from plants to bacteria is extremely low under natural conditions (Nielsen *et al.* 2000, Thomson 2000).

Experience over the last 50 years with organisms such as *Agrobacterium* species in the field has not shown any cases where genes have transferred from crop to weed via bacteria or any other vectors. Of the millions of herbicide resistant weeds which have appeared over the last 30 years, all can be traced to mutation, selection and evolution and not to plasmid-mediated horizontal gene transfer (Gressel and Rotteveel 2000).

If herbicide resistance could be horizontally transferred, ‘plants-at-risk’ of becoming herbicide tolerant increases from the wild and weedy relatives of crop species to a much wider range of plants. The consequences of any such transfer will depend on environmental and herbicide use patterns. Current scientific evidence is that horizontal transfer of genes from genetically modified crops to other plants is extremely unlikely.

Natural selection for herbicide resistant weeds

Herbicide resistant weeds have been emerging over the past 30 years and have been found to be due to natural selection, rather than gene transfer or outcrossing (Gressel and Rotteveel 2000). Each population of a weed contains plants with variable resistance to particular herbicides, a characteristic used to breed herbicide resistant plants by traditional techniques. With repeated applications of the same herbicide, susceptible plants are killed while herbicide resistant plants survive and reproduce. Over time, the balance of the population can shift from the original position of mainly susceptible plants to an increased proportion of resistant individuals (Pratley *et al.* 1998).

Weeds evolve resistance to particular herbicides at varying rates (Shaner *et al.* 1996). The variation depends partly on characteristics of the weed population, including the initial variation in herbicide resistance in the population, the number of weeds present, the rate at which the weed population mutates and the efficiency of plant reproduction. When weed seeds can survive for a long time in the soil, the germination of susceptible seeds tends to dilute the development of resistant weeds. Whether the herbicide resistance makes plants more or less fit when herbicide is not applied also affects the speed at which herbicide resistant weeds develop. The rate of emergence of herbicide resistant weeds also depends on the selection pressure placed on the weeds for herbicide resistance, which depends on the frequency, amount and types of herbicide used and agricultural practices (Pratley *et al.* 1998).

In 1997, an international survey found 216 herbicide-resistant weed types in 45 countries (Heap 1997). Since 1978 the number of *new* herbicide-resistant weeds has increased at a relatively constant rate, at an average of nine new cases per year around the world. There are now 248 weed species that have evolved resistance to one or more herbicides (Heap 2001; Table 4).

The problems posed by the herbicide resistant weeds depend on their location, the area they cover and the availability of alternative herbicides to control them. For example, the most widespread weed resistance problem is triazine resistant weeds, which cover more than three million hectares worldwide. Sixty three different triazine resistant weeds have been identified in 25 countries, mostly in maize crops in the USA and Europe or in European orchards. Although widespread, these weeds have been controlled successfully in many countries by the use of alternative herbicides (Heap 1999, 2001). Other emerging weeds can be controlled by the use of management practices which rotate herbicides. The fastest growing group of herbicide resistant weeds over the last 10 years is those resistant to acetolactate synthase inhibitors (Australian group B), the most commonly sold herbicides globally. The weeds have appeared in cereals, maize/soybean rotations, rice, on road sides and in forests (Heap 1999). However in Europe, where herbicides are rotated, few weeds have evolved resistance to these herbicides (Gressel and Segel 1990).

Weeds can become a problem if they cover a large area and there are few alternatives available. For example, 25 grass species have developed resistance to acetyl-coenzyme A carboxylase inhibitors (Australian group A) herbicides, which provide excellent grass control in cereal and other crops. These weeds are of major economic importance globally because of the large areas infested and the limited number of alternative herbicides available for weed control (Heap 1999). Food production in developing countries may be seriously affected by several urea-resistant weeds, particularly chlorotoluron-resistant *Alopecurus japoniens* in Chinese wheat fields and isoproturon-resistant *Phalaris minor* in Indian wheat fields (Heap 1999).

Other groups of herbicides are associated with few weed problems. These include dinitroaniline herbicides, which have been used for more than 25 years for pre-emergence weed control in cotton, soybeans, wheat and canola crops. Despite their long persistence and extensive use, only 10 weeds have evolved resistance to these herbicides (Heap 2001). Glyphosate is also considered a low risk herbicide for the evolution of herbicide resistance because of its mode of action, chemical structure, limited metabolism in plants, use pattern, and lack of residual activity. Despite a long history of extensive use only three weeds, annual or rigid ryegrass (*Lolium rigidum*), horseweed and goosegrass, have evolved glyphosate resistance (Heap 2001).

Table 4: Herbicide resistant weeds recorded around the world

Australian group	Principal mode of action	Chemical families	Number of resistant weed species
A	Inhibitors of fat (lipid) synthesis by inhibiting acetyl CoA carboxylase (ACCase)	Arlyoxyphenoxypropionates ('FOPS'), Cyclohexanediones ('DIMS')	25
B	Inhibitors of acetolactate synthase (ALS)	Sulfonylureas , Imidazolinones, Sulfonamides	68
C	Inhibitors of photosynthesis at photosystem II	Triazines , Triazinones, Uracils, Pyridazinones	63
		Ureas	20
		Nitriles, Benzothiadiazoles, Phenyl-pyridazines	1
D	Inhibitors of tubulin formation	Dinitroanilines, Pyridazines	10
E	Inhibitors of mitosis	Thiocarbamates, Carbamates, Organophosphorous	7
F	Inhibitors of carotenoid biosynthesis	Nicotinanilides, Triazoles, Pyridazinones	6
G	Inhibitors of protoporphyrinogen oxidase	Diphenyl ethers, Oxadiazoles	0
H	Inhibitors of protein synthesis	Thiocarbamates	0
I	Disruptors of plant cell growth (hormone mimics)	Phenoxys, Benzoic acids, Pyridines	20
J	Inhibitors of cell wall synthesis	Alkanoic acid	0
K	Herbicides with multiple sites of action	Amides, Carbamates, Amino propionates, Benzofurans, Phthalamates, Nitriles	3
L	Disruptors of photosynthesis at photosystem I	Bipyridyls	21
M	Inhibitors of the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS)	Glycines	3
N	Inhibitors of glutamine synthetase	Glycines	0
	Unknown		1
Total			**248**

Source: Heap 2001

Herbicide resistant weeds have developed to a number of other herbicides, including those for which transgenic herbicide resistant crops are being developed (see Table 4).

Herbicide resistant weeds have the greatest economic impact on crop production when there are few or no alternative herbicides to control resistant weeds, and those with multiple resistance are the greatest concern to farmers. These usually result from the use of two or more herbicides selecting for two or more resistance mechanisms. Transgenic herbicide tolerant crops will need to be used in rotation with conventional cultivars and in conjunction with non-chemical weed control and different herbicides to avoid the selection of herbicide resistant weeds.

Herbicide resistant weeds in Australia

The risk of herbicide tolerance gene transfer

Assessing the risk of herbicide tolerance genes transferring to closely related species requires an assessment of species related to crop species. Australia grows 235 crops (Lazarides and Hince 1993), of which 22 per cent have no relatives in this country and are considered not to behave as weeds themselves (Sindel 1997). An additional 17 per cent have no weedy relatives other than the crop itself, as a volunteer weed, naturalised plant or weedy race of the species. Almost 61 per cent of all the crops have more than one weedy relative, with up to 58 for potatoes (*Solanum tuberosum*) and eggplants (*Solanum melongena*). Sindel (1997) classified Australian crops according to the potential of an inserted gene crossing to a weedy relative (Table 5). The high risk plants have weedy relatives in the same species, high numbers of weedy relatives and/or evidence of reproductive compatibility with widespread weeds. Low risk crops have insignificant or no weedy relatives in Australia.

Table 5: The risk of a gene crossing from a crop to a wild relative in Australia

Risk	Plant species
High	Asparagus, barley, cabbage, canola, capsicum, celery, carrot, lettuce, linseed, oats, onion, parsnip, potato, radish, rice, silver beet, sorghum, subterranean clover, sunflower, tobacco, vetch, white clover.
Medium	Cucumber, faba bean, lucerne, lupin, mung bean, rye, safflower, sweet potato, watermelon.
Low	Bean, buckwheat, chickpea, cotton, maize (corn), pea, peanut, pumpkin, soybean, sugarcane, tomato, triticale, wheat.

Source: Sindel 1997

The escape of herbicide tolerance genes to wild, weedy plants could cause severe weed problems and pose a real threat to the efficacy of herbicides as a weed control option. Management action can be taken to reduce the risk of herbicide tolerance genes transferring to weeds and the impact if they do escape. Avoiding high risk crops for genetic modification is one method of ensuring there is no gene transfer. Introducing compatibility and fertility barriers with herbicide tolerance will also reduce the risk of genes escaping into weeds. Another method to reduce the risk is to physically separate the crop from compatible wild relatives. Determination of the separation distance requires knowledge of pollen dispersal, wild plant distribution and interfertility relationships. It will also be affected by pollinators, winds, intervening vegetation and changes in the distributions of the wild plants and crop species over time. Other strategies, such as adjusting flowering times, are considered more variable and less reliable (Keeler *et al.* 1996).

Cultural practices such as complete harvesting of the crop before flowering and surrounding the transgenic crop with the traditional, susceptible crop may also reduce the risk of outcrossing herbicide tolerance into related weeds. Mitigation strategies designed to impede the survival and spread of selected herbicide resistant weeds should also be effective in reducing the impact of outcrossed herbicide resistant weeds. These strategies involve rotating herbicides, mixtures and mechanical cultivation and are more effective with early detection of the weed problem (Keeler *et al.* 1996).

Selecting herbicide resistant weeds

Most herbicide resistant weeds have been selected for, rather than developing from the transfer of genes. Many of these herbicide resistant weeds have been identified in Australia. The first was annual ryegrass (*Lolium rigidum*) resistant to diclofop-methyl, a group A herbicide (Heap 1999). By 1991, seven weeds had been found to be resistant to at least one herbicide, with 20 identified by 1999 and currently 25 Australian weed species have been identified as herbicide resistant (see Appendix 3).

In Western Australia, the herbicide resistance problem in cropping is by far the most severe in world agriculture (Powles 1999). Herbicide resistant weeds are now estimated to occur over 500,000 hectares or 10 per cent of the cereal cropping area of Western Australia (Cullen *et al.* 1995). Resistance is by far the biggest problem in annual ryegrass (*Lolium rigidum*) and is emerging in wild radish (*Raphanus raphanistrum*), the other major weed of Western Australian agriculture (Powles 1999).

Annual ryegrass that develops resistance to one herbicide can exhibit multiple herbicide resistance, often to a wide range of herbicides. In the worst case, ryegrass can be resistant to 6 different groups of herbicides (see Appendix 3). The increasing use of different herbicides, such as triazine (Group C) on canola and trifluralin (Group D), increases the opportunity for other resistant weed problems to develop. Many of these weeds will have multiple resistance to other herbicides and will be a major challenge to intensive cropping in Western Australia (Powles 1999). Trifluralin resistance in annual ryegrass has already been identified across southern Australia, including Western Australia (Sutherland and Lemerle 1998).

Western Australian grain farmers continue to rely on glyphosate and paraquat for knock-down weed control before seeding and for crop and pasture-topping. Recently (in 1996, 1998 and 1999) glyphosate resistant annual ryegrass (*Lolium rigidum*) was discovered at Echuca, Victoria and Orange, New South Wales and in the north west of New South Wales (Pratley *et al.* 1996; Powles *et al.* 1998; Australian Broadcasting Corporation 1999c). A recent survey found glyphosate resistant ryegrass at eight sites in Australia (Australian Broadcasting Corporation 1999a). Glyphosate resistant ryegrass in Western Australia will add to an already complex weed problem and a recent report indicates that this herbicide resistant weed has developed (Australian Broadcasting Corporation 2001). Western Australia has similar problems with wild radish (*Raphanus raphanistrum*) developing resistance to herbicides. Resistance to sulfonylurea (group B) herbicides has been found in 36 populations of weeds with two highly suspect populations being studied for triazine (Group C) resistance (Powles 1999).

'The challenge for grain growers is to use herbicides sustainably' (Powles 1999) and avoid the development of herbicide resistant weeds. The key to slowing the development of herbicide resistant weeds is an effective weed management strategy. This may involve reducing dependence on herbicides, rotating herbicides and using a variety of weed control methods (Powles 1999). Effective weed control strategies are based on preventing weed seeds or vegetative reproductive parts moving into the soil. Preventing immigration of new seeds into the fields and reducing seed production of weeds will reduce the weed burden. Planting clean seed, cleaning agricultural machinery between fields, preventing grain escaping during transport and controlling weeds along roads, fences and waste areas all contribute to weed control. Crop practices such as herbicide use, tillage, stubble burning and agronomic factors such as crop cultivators used, crop rotations, weed and crop densities, emergence times for the crop and weeds, row spacing, fertility and fertiliser use will all affect weed management (Thill 1996).

Other risks

Other possible adverse effects from the use of transgenic herbicide tolerant crops have been identified by a number of people. These include the potential for the genetic diversity of crop and other species to decrease; the potential for herbicide tolerant crops to be more demanding of soil nutrients or more susceptible to diseases or pests; the potential to enable agriculture to proceed beyond sustainable limits; the possibility that pesticide use will increase with the adoption of herbicide tolerant crops rather than decreasing, and a threat to biodiversity by the introduction of foreign genes into native species ('genetic pollution').

Decreasing genetic diversity

Genetic modification is undertaken on a restricted number of crop cultivars, usually derived from developed countries. Widespread adoption of a limited number of cultivars of transgenic crops could reduce the genetic diversity of crop species (Hamblin and Atkins 1995). Genetic variation within species enables crops to adapt to a variety of environments and climates. Genetic conformity (especially if seeds from transgenic crops cannot be stored and sown in following years) will decrease the diversity of crop cultivars in use, which may affect the ability of crops to adapt to specific environmental conditions or to changing conditions such as those expected with global warming. Similarly, genetic diversity also gives plants some protection against diseases and pest problems and variation in levels of soil nutrients. Cultivars selected for genetic modification may not be the most appropriate for large areas of agricultural land with different characteristics from the site where the cultivar was chosen. While seed banks such as the National Germplasm Repositories in the United States of America and the N.I. Vavilov All-Russian Scientific Research Institute of Plant

Industry preserve genetic material from a number of crop cultivars from around the world, it would take time for the varieties to be tested and seed stocks grown to substitute for existing cultivars if environmental conditions change.

Transgenic crops could decrease biodiversity, including on-farm conservation, via the management methods required to grow the crops. For example, a weed management strategy which involves careful weed control around the crop could affect populations of native plants and animals which survive on farms.

These risks need to be considered in the context of other risks to biodiversity such as decreasing wilderness areas, introduced pests and environmental pollutants. Increases in agricultural land productivity through transgenic crops may actually contribute to increasing biodiversity in non-farm environments, by reducing the pressure to transform wilderness areas into farmland.

Commercial risks

There are commercial risks to farmers in growing any crop, including transgenic crops. The following factors need to be considered:

- the additional cost of transgenic seeds
- the potential market for the crop and its requirements;
- the potential price for the crop
- the cost and convenience of required management systems, such as weed management strategies for herbicide tolerant crops
- the estimated pest and weed problems
- possible contractual commitments.

One risk is that the yield from the transgenic crop in a particular environment may not be as high as from current cultivars or not sufficiently superior to make the transgenic crop an economic proposition. For example, *Bt* (*Bacillus thuringiensis* - insect resistant) cotton was found to have less benefit to Australian farmers than those obtained by American farmers (Foster and Rees 1998). A yield problem was discovered with a new two-gene, insect resistant cotton being developed by Monsanto, where the company found a 22 per cent decrease in yield and ceased its development (Australian Broadcasting Corporation 1999b). Factors such as disease resistance and the ability to utilise soil nutrients will influence crop yields and farmers' incomes.

Another major commercial risk of embracing transgenic crop technology is that of alienating existing agricultural markets opposed to the use of the technology. The Grains Council of Australia recommended that genetically modified grain be segregated from unmodified grain to keep European and Japanese markets, which are opposed to genetically modified food, happy (Lush 1999). Segregation of genetically modified grain from conventional grain would enable these markets to be met from conventional grain supplies, whether required by preference or import restrictions. Some markets may also require the labelling of food derived from transgenic crops. In

Australia, gene technology labelling regulations were introduced in December 2001. Japan has also introduced labelling requirements for GM food and Europe is in the process of formulating its requirements. It is not known what the effect of these labels on these markets will be.

Although it is claimed herbicide tolerant crops will reduce herbicide use, farmers may become dependent on the herbicide tolerant crop and its associated herbicide with a resulting increase in the use of particular herbicides. For example, the use of herbicide tolerant soybeans in the US was expected to decrease the amount of herbicide used but this promise is yet to be fulfilled. The pattern of herbicide use has changed but the amount applied has not decreased (Gianessi and Carpenter 2000). The effect of the herbicides on the environment should also be considered. The processes determining the fate of herbicides in the environment include retention in the soil (adsorption, desorption and strong binding), chemical and biological degradation in air, soil and water and the transportation processes in air and water (evaporation, run-off and leaching). To predict the environmental fate of herbicides requires knowledge of these processes, methods and timing of herbicide applications, crop production practices, soil and landscape properties, and sometimes site-specific knowledge. The environmental effect of a herbicide also depends on the distribution of residues and their toxicity (Moorman and Keller 1996).

Another risk of transgenic herbicide tolerant crops is that they may be too successful, in that they could enable agriculture in many sites now considered unsuitable. While there could be short-term increases in agricultural production, the longer term damage from inappropriate and unsustainable agriculture could decrease food production over time. This emphasises the need for the use of transgenic crops, as with all other agricultural practices, to be sustainable.

Recent years have seen the consolidation of multinational companies' control of global food production, with the acquisition of seed companies, agricultural chemical companies and intellectual property over technologies such as transgenic herbicide tolerance. Adoption of new techniques owned by these companies around the world could enable manipulation of a greater proportion of the world's food supply. With ownership of a greater proportion of the agricultural production chain (seeds, herbicides and fertilisers) pressure to develop new technologies such as a new generation of herbicides with better agronomical and environmental characteristics may decrease, or their marketing may be inhibited by a need to recoup investments in the current technology.

There is also a risk that the use of herbicide tolerant crops will advantage both Australian agriculture and our major competitors, the USA and Europe, with our competitors' 'high input' agriculture gaining more from the technology than Australia's 'low input' agriculture, thereby reducing the competitiveness of Australia's agriculture (Urban 1999).

Having identified a number of risks and benefits of transgenic herbicide tolerant crops, examining the history of growing herbicide tolerant crops over the last five years, mainly in the USA, may indicate potential advantages and disadvantages for Australian agriculture.

5. Commercial experience with transgenic herbicide tolerant crops

Transgenic crops were introduced commercially in 1995. Since then the area planted per year has increased from 1.7 million hectares in 1996 to 52.6 million hectares in 2001 (James 2001). Over three quarters of the transgenic crops have been herbicide tolerant (see Table 1). Over half of the global transgenic crops have been grown in the USA, with Canada growing another quarter. The experience from these two countries may indicate potential risks and benefits to Australian agriculture from the use of transgenic herbicide tolerant crops.

Experiments on the environmental risks and benefits are lacking but existing studies show that the risks and benefits can vary depending on location and season, and according to the trait and cultivar modified (Wolfenbarger and Phifer 2000). Wolfenbarger and Phifer (2000) looked at the following risks of transgenic crops which are relevant to herbicide tolerant crops: risk of invasiveness; possible effects on soil ecosystems, indirect effects on seed eating birds and variability and unexpected results.

While little is known of the potential ecological consequences of genes transferring from commercial genetically modified crops to wild relatives, past experience with conventional crops suggests that negative effects are possible (Wolfenbarger and Phifer 2000). Long term cultivation of crops has shown that hybridisation occurs between crop species and wild plants. Within the scientific community, the relevant concern is not whether the genes will move, but whether they will thrive in the wild and how they might increase the ‘weediness’ of particular wild plants by making them more difficult to control (Ervin *et al.* 2000). Ecologists tend to be more concerned about wild relatives that gain genes for insect or virus resistance because they provide a fitness advantage but there is also a concern that in situations where herbicides are used to control weeds, herbicide tolerance could confer a competitive advantage (Keeler *et al.* 1996).

Following the commercial release of herbicide tolerant crops, some herbicide tolerant volunteer weeds have been discovered. These have been caused mainly by the herbicide tolerant crop pollinating other varieties of the same crop but at least one case appears to originate from a seed which was moved between fields. The first report of a herbicide tolerance gene transferring was from northern Alberta, where the glyphosate-tolerant trait appears to have been transferred by pollen from a Roundup®-tolerant canola (Quest) into glyphosate-sensitive canola lines called Innovator and 45A71 (MacArthur 1998). Since then, canola that is tolerant to three herbicides - glyphosate, glufosinate and imidazolinone - has been discovered in Alberta (Hall *et al.* 2000). The triple tolerant plants were found to be mainly the result of pollen transfer, including one case of pollination over 550 metres (Westwood 2001). While the use of the three different herbicide tolerant varieties at the same time would be unusual, the example shows how rapidly genes can move in outcrossing species, such as canola, and why planting distances and crop rotation precautions and herbicide/weed control techniques need to be varied regularly to avoid developing problematic volunteer weeds (Westwood 2001). Transfer of herbicide tolerance traits to wild relatives, while possible, is expected by some to be less frequent than this crossing between varieties of the same species and the resulting hybrid plants may suffer from lack of vigour or fertility (Westwood 2001), although others have found the hybrids may not differ from non-transgenic plants in survival or number of seeds per plant (Snow *et al.* 1999).

Some indirect effects could also be associated with using herbicide tolerant crops. Watkinson *et al.* (2000) predict that the more effective weed control offered by herbicide tolerant crops could lead to lower food availability for seed eating birds. Effects this may have on bird populations depends on a number of factors, including how farmers adopt the new technology, as well as the improvements in weed control.

Ecosystems are complex and not every risk associated with the release of new organisms can be identified, much less considered. Environmental and cultivar variability complicates the task of assessing risk. A single transgenic herbicide tolerant crop will potentially interact with a diversity of habitats in time and space, so the potential risks from the crop may vary accordingly (Wolfenbarger and Phifer 2000).

The benefits gained by using transgenic herbicide tolerant crops have been slightly better studied than the ecological risks. The use of herbicide tolerant crops may lead to environmental benefits by encouraging farmers to adopt conservation tillage practices which decrease soil erosion and water loss and increase soil organic matter. Studies do not appear to have been done to discover whether these expected improvements in soils are occurring when herbicide tolerant crops are used (Wolfenbarger and Phifer 2000).

The yield and potential benefits and costs of genetically modified crops, like that of traditionally bred crops, vary with the season, region, prices and costs. There have been a number of studies to examine the effects of growing genetically modified crops on crop yields and farmers' profitability. The published independent studies show there are differences between the different genetically modified crops, between individual farmers' returns for the same crop and seasonal variations in pest and weed problems which affect the profitability of crops. This variation is often not reported but is of vital interest to farmers who must make a decision about introducing the technology and incur costs before knowing pest and weed levels for the season.

The studies below are considered to be the more reliable ones but they cover only the first few years of the technology. An accurate assessment of the contribution of a new technology to farm profitability would require a decade or more of actual field use. Environmental and economic conditions that face farmers vary widely from year to year and only in a long term assessment do the underlying trends become obvious. Given the recent introduction of agricultural biotechnology, this is not yet possible.

Commercial return from growing GM soybeans

The most extensively used, and studied, commercial genetically modified herbicide tolerant crop is soybeans in the USA. Gianessi and Carpenter (2000) found that from 1995 to 1998 the promises of decreased herbicide use on soybeans were not fulfilled but that the herbicides moved towards those considered less harmful to the environment, such as glyphosate (Roundup®), and the number of applications decreased, which made management easier. Wolfenbarger and Phifer (2000) agree there were fewer applications but point out that more herbicide was applied per acre. The increase in herbicide use was mainly due to a seven-fold increase in the use of glyphosate per acre, smaller increases in seven other herbicides and decreased use of 16 other herbicides.

Over the time studied, all soybean farmers benefited from herbicide manufacturers dropping their prices, some by as much as 40 per cent, because of competition for herbicide sales. Price changes alone accounted for savings of about $US 254 million per year from 1995 to 1998, even if herbicide use patterns had not changed. With the changed herbicide use patterns, farmers saved $US 380 million per year on weed control costs but paid annual technology fees of $US 160 million, resulting in a net gain of $US 220 million per year (Gianessi and Carpenter 2000).

Studies on the yield of herbicide tolerant soybeans, compared to the conventional varieties have been undertaken by a number of groups, including universities and the developers of the transgenic varieties. Oplinger *et al.* (1998) found that yields from herbicide tolerant soybeans were, on average, 4 per cent lower than yields from conventional varieties. In contrast, Monsanto, the main developer of genetically modified soybeans, has reported there is no difference in the yields of herbicide tolerant soybean and their conventionally bred equivalents (Delannay *et al.* 1995). An analysis of a number of trials undertaken in 1998 and 1999 has found that the herbicide tolerant soybeans yield from 82 per cent to 109 per cent of that of conventionally bred soybeans in different areas, averaging 97 per cent in 1999 (Carpenter 2001a). This has been interpreted by some as an inherent problem of genetically modified plants, due to the process of genetic modification itself (Benbrook 1999; Ervin *et al.* 2000). An alternative explanation is that herbicide tolerance genes have not been inserted into the highest yielding varieties, so the yield from herbicide tolerant crops is not as high as that which can be obtained from conventional varieties. Over time, the herbicide tolerance gene is being introduced into more varieties of soybean and the yield is expected to increase (Carpenter 2001a).

Trials to estimate the returns from growing genetically modified herbicide tolerant soybeans have had variable results. Some show that the herbicide tolerant soybean with Roundup® tolerance was a more profitable system (eg Roberts *et al.*1999), some show little difference (eg Duffy and Ernst 1999) and others show that conventional varieties are more profitable (eg Webster *et al.* 1999). Experience from the field is difficult to interpret because there are a number of factors that affect which farmers grow the new varieties, including the size of the operation and the education level of the farmer, which also affect farm profitability.

The primary reason US growers have adopted herbicide tolerant soybean varieties is the simplicity of the weed control program (Carpenter and Gianessi 2001). The system of using a single herbicide provides improved weed control, less crop injury, more flexibility in applying treatments and less concern about the herbicides used. In addition, the herbicide tolerant seed is competitively priced (Gianessi and Carpenter 2000). The main advantage of the herbicide tolerant soybean system is the ease of management, rather than increased returns to farmers.

Commercial return from growing GM cotton

Herbicide tolerant cotton is also grown extensively in the USA. Two genetically modified herbicide tolerant cotton varieties are available, bromoxynil (Buctril) tolerant cotton has been available since 1995 and glyphosate (Roundup®) tolerant cotton since 1997. In 2000, 7.2 per cent of the US cotton area was planted with bromoxynil tolerant cotton and 54 per cent with glyphosate tolerant cotton. A new herbicide (Staple), a selective broadleaf herbicide that can be applied at any post emergent stage of cotton, became available in 1996. This has given US cotton farmers three new post emergence broadleaf weed control systems (Carpenter and Gianessi 2001).

Herbicide use was expected to decrease with the widespread use of herbicide tolerant varieties. Any change in herbicide use due to the new crops in the US cotton industry has been difficult to detect because the herbicide Staple, which also decreases the total amount of herbicide used, was introduced at the same time as the herbicide tolerant crops. Much of the decline in the amount of herbicide used on the US cotton crop since 1995 is thought to be due to the adoption of the new herbicide and probably not to the introduction of the new cotton varieties. The decrease seen in the number of applications of herbicides is thought to be due to increasing adoption of the herbicide tolerant cotton varieties (Carpenter and Gianessi 2001).

Some US cotton growers have realised cost savings by switching to glyphosate tolerant cotton but others have found it to be more expensive. This depends on the number of applications of herbicide required and other treatments, such as soil applied or post emergence treatments required. A study of the cotton varieties and weed control systems found the yields varied from 93 per cent to 102 per cent of conventional systems (Carpenter and Gianessi 2001). The net returns to farmers was found to vary with the system used and to vary between States, for example the Staple system was found to reduce returns to the farmer in Tennessee but increase returns in Louisiana whereas the Roundup Ready® system, with herbicide applied as needed, increased returns in Tennessee and reduced returns in Louisiana (Carpenter and Gianessi 2001). At this stage, there appears to be no clear advantage of one system over another (Carpenter and Gianessi 2001). As with soybeans, the uptake of this new technology in the cotton industry has been driven largely by the ease and convenience of the weed control systems (Carpenter and Gianessi 2001).

Commercial return from growing GM canola

Canada is a major grower of the worlds' canola and has introduced a number of herbicide tolerant varieties. These have been developed using both modern gene technology (for example, glyphosate tolerant canola) and more conventional techniques (for example, Smart canola, which is resistant to Pursuit). In 1999, about 55 per cent of the Canadian canola crop was genetically modified (see Table 6).

Table 6: Western Canada 1999 canola crop

Variety	GM canola (glyphosate tolerant)	GM canola (glufosinate tolerant)	Non-GM canola (Smart tolerant)	Conventional canola	Total canola crop
Approximate area (thousands of acres)	5 000	2 600	2 600	3 600	13 800
Proportion of the crop	37%	19%	19%	26%	

Source: Alberta Canola Producers Commission 2000

Fulton and Keyowski (1999) found in a two-year study that the benefits of herbicide tolerant canola varied. Some farmers benefit from adopting the technology, while others do not. Generally, the farmers who have not adopted conservation practices do not obtain the same agronomic and economic benefits of herbicide tolerant canola as to those farmers who have adopted conservation practices. While the new herbicide tolerant systems can mean less money is spent on herbicides, the increased cost of seeds and lower yields may mean the gross return is less than with conventional crops.

The Canola Council of Canada (2001a) commissioned a study on the agronomic and economic impacts of transgenic canola. The study did not include Smart varieties, which are herbicide tolerant but not transgenic. Six hundred and fifty canola growers in western Canada were surveyed on their attitudes, production practices and production costs. Thirteen growers who produced both transgenic and conventional varieties provided detailed information on their production and costs from 1997 to 2000.

The main reason canola growers chose transgenic varieties was the easier and better weed management (50 per cent), with better yield, better return, more profit (19 per cent) and for specific weed problems (grass or broadleaf weed control, 18 and 15 per cent respectively). Cost was the main reason growers chose not to grow transgenic canola – i.e. cost of the technology or cost of implementing the management system. Some growers (16 per cent) were concerned about market access for genetically modified canola (Canola Council of Canada 2001a).

The net returns for growers ranged from losses of $80 per acre to profits of $240 per acre for transgenic varieties and from losses of $120 per acre to profits of $180 per acre for conventional varieties. The average direct costs of the transgenic systems were greater but so were the average returns. Growers reported an average $5.80 per acre increase in net return on their transgenic crops compared to conventional acres in

2000. The higher returns were due to higher yields and less dockage and lower herbicide and tillage costs. Seed, fertiliser and the costs of using the gene technology were higher for transgenic crops than for conventional crops. The 13 case studies found that growing transgenic canola provided higher gross returns but greater variable costs. In three of the four years, the increased revenue compensated for the increased costs but this was not the case for the fourth year. The revenue and costs from growing canola vary significantly from year to year, as do the differences between conventional and transgenic varieties (Canola Council of Canada 2001a).

Canadian canola growers policy is that ‘Producers determine which crop to grow based on their own production cost. They evaluate the potential crop price, determine their production cost, their anticipated yield and grow the crop that will provide the highest net return per acre. Producers also evaluate the cost of growing genetically modified varieties versus conventional varieties of canola to determine the most cost effective crop to produce on their farm. Genetically modified crops can sometimes result in higher canola yields especially under high weed pressure. Higher yields versus production costs must be evaluated to determine crop profitability.’ (Canadian Canola Growers Association 1999).

6. Conclusion

At their best, transgenic herbicide tolerant crops could contribute to the sustainability of agriculture by reducing herbicide use and off-farm environmental impacts, increasing profitability and markets for agricultural products and more efficiently utilising the natural resources essential to agriculture. If not managed effectively, GM herbicide tolerant crops could add to herbicide resistant weed problems. In the long term, the impact of transgenic herbicide tolerant crops in Australia depends on which transgenic crops are used, how they are incorporated into agricultural systems and how the risks are managed.

In the past, risk management was something undertaken by governments, who assessed the risks, considered policy options and announced their decisions. Recently, risk management has broadened beyond regulatory actions taken by federal, state and local government agencies because government risk managers now consider regulatory and voluntary approaches to reducing risk and because others, including individuals, businesses and industries, conduct risk management activities (Omenn *et al.* 1997).

Used wisely, transgenic herbicide tolerant crops have the potential to reduce the amount of herbicide used and to encourage farmers to switch to less toxic, less persistent herbicides. They could then contribute to global pesticide risk reduction. However, the use of herbicide tolerant crops also has the potential to increase reliance on herbicides for weed control in agriculture and adversely affect pesticide risk reduction strategies. The final outcome will be determined by how the crops and associated pesticides are actually used.

An Australian herbicide resistance management strategy was developed in 1995 to minimise the risk of weeds becoming resistant to a single herbicide or herbicide group: ‘Widespread development of herbicide resistance in weeds has the potential to jeopardise the sustainability of Australian cropping systems’ (Matthews and Powles 1992). The strategy encourages farmers to rotate herbicides to avoid herbicide resistant weeds developing, because ‘Resistance is the inevitable result of persistent herbicide use on weed populations’ (Matthews and Powles 1992). Herbicides are classified by their mode of action (see Appendix 1) and the herbicide group must appear on the label. This enables farmers to distinguish herbicides with different modes of action and vary the group of herbicides used to reduce the risk of herbicide resistant weeds emerging.

Individual farmers, or groups of farmers can also implement ‘integrated weed management’ programs. Using an integrated range of weed control techniques, rather than herbicides alone, can also slow the development of herbicide resistant weeds. ‘Integrated weed management is the planned and managed use of physical, chemical and biological measures to control specific weeds or weed populations’ (Powles and Matthews 1996). Integrated weed management requires an understanding of, and then uses, the biological characteristics of all species and their dynamics within the agricultural ecosystem. It may include non-chemical means of controlling weeds such as grazing, burning, ploughing, biological control, collecting weed seeds during harvest and rotating crops.

The cropping system itself can also be managed to discourage the emergence of herbicide resistant weeds because it determines the niches available for weeds to develop and flourish. Crop rotations should be designed to be disruptive and not selective. They need to minimise the development of resistance to herbicides and to other control measures (Bowran *et al.* 1997). The cropping system needs to be managed on a farm scale and on a regional scale to minimise the emergence of herbicide resistant weeds and volunteer weeds.

Farmers are vital to the successful implementation of programs to manage many of the risks associated with herbicide tolerant crops. As commercial transgenic herbicide tolerant crops become available, farmers will have to decide whether they want to grow them. Farmers are asking for unbiased information to assist them to make this decision with confidence (Coakes and Fisher 2001). The type of questions they have asked includes:

- What are the potential environmental benefits and costs from growing genetically modified crops?
- Will I be able to sell my product?
- Will I get a premium for genetic modification-free or will I be penalised for genetically modified product?
- Will genetically modified crops give me better yields and, if so, how much better?
- Will it cost me more to grow genetically modified crops?
- Will I have to implement different management systems?
- Will I have to sign a contract with the seed supplier or the seed developer?
- Who can I trust to get balanced information from?

In most cases, comparisons between conventional and genetically modified crops are wanted. This volume provides some information on the possible risks and benefits of transgenic crops but is not able to answer many of the questions farmers are asking. Market information, particularly about premiums or penalties, is usually anecdotal and markets can vary quickly. Information to answer the remaining questions depend on the particular crop and genetic modification being considered and can only be answered once the crop has been approved for commercial use (for example, information about required management systems) or has been in use for some time in a variety of conditions (for example, information on crop yields or costs).

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Glossary

Adsorption	A process where an extremely thin layer of molecules sticks to the surfaces of solid bodies or liquids with which it is in contact.
Agrobacterium tumefaciens	A soil bacterium used for inserting genes into plants.
Allergen	Any substance which can induce an allergy, that is, an abnormal immunological reaction to a substance.
Biotechnology	The use of biological substances to perform specific industrial or manufacturing processes. It includes the modern processes of ‘gene technology’ and the much older processes of bread, wine, beer and cheese making.
Bromoxynil	A herbicide which inhibits photosynthesis at photosystem II (in group C of the Australian classification of herbicides by mode of action, see Appendix 1). Brands available in Australia include Buctril’ and Koril’.
Carcinogen	A substance which tends to produce a cancer.
Chloroplast	An organelle in plants and some bacteria which produces energy by photosynthesis.
Chlorsulfuron	A herbicide which inihibits the enzyme acetolacatate synthase (in group B 1 of the Australian classification of herbicides by mode of action, see Appendix 1). Examples available in Australia include Glean’ and Nufarm Siege Cereal Herbicide’.
Chromosomes	The self-replicating genetic structures of cells containing the cellular DNA that bears in its nucleotide sequence the linear array of genes.
Dalapon	A herbicide which inhibits fat synthesis (in group J of the Australian classification of herbicides by mode of action, see Appendix 1). Examples available in Australia include Graypon Grass Killer ’ and Propon 2,2-DPA Systemic Grasskiller ’.
Deoxyribonucleic acid (DNA)	The molecule that encodes genetic information. DNA is a double-stranded molecule held together by weak bonds between base pairs of nucleotides. The four nucleotides in DNA contain the bases: adenine (A), guanine (G), cytosine (C), and thymine (T). In nature, base pairs form only between A and T and between G and C; thus the base sequence of each single strand can be deduced from that of its partner.

Desorption	A process where an extremely thin layer of molecules comes away from the surfaces of solid bodies or liquids with which it is in contact. It is the reverse of adsorption.
Detoxification	Making a harmful substance harmless.
Dicotyledons	A subclass of plants. They tend to have broad leaves, two seed leaves, netlike veins in the leaves, flower parts are usually in fours or fives, a ring of primary vascular bundles in the stem and a taproot system.
Electroporation	The process where an electric pulse is used to increase the permeability of the cell membrane.
Enterococci	Bacteria normally found in the faeces of most humans and many animals. They are found in normal, healthy people but occasionally cause disease, including urinary tract and wound infections.
Fluazifop	A herbicide which inhibits fat (lipid) synthesis. They are in group A of the of the Australian classification of herbicides by mode of action (see Appendix 1) and include Fusilade’ and Fusion’.
Gene	The hereditary determinant of specific differences between individuals. It can increasingly be identified, using biotechnology, as a specific sequence of nucleotides.
Gene technology	The processes which enable genes to be moved from one organism to another, often unrelated, organism.
Genome	All the genetic material in the chromosomes of a particular organism.
Glutamate	Group of herbicides which inhibit glutamine synthesis. They are group N of the Australian classification of herbicides by mode of action (see Appendix 1) and include Basta’ and Liberty’.
Glycoalkaloids	Naturally occurring toxins which can be found in potatoes. They can affect quality and taste and are considered unsafe for humans at high levels.
Glyphosate	Herbicides which inhibit EPSPS (the enzyme 5-enolpyruvylshikimate-3-phosphate synthase). They are in group M of the Australian classification of herbicides by mode of action (see Appendix 1) and include Roundup’ and Zero’.
Herbicide	A chemical used to kill or control the growth of plants.

Herbicide resistance	Herbicide resistance is the inherited ability of a plant to survive and reproduce normally following exposure to a dose of herbicide normally lethal to the wild type (Heap 1999). It is often used interchangeably with herbicide tolerance.
Herbicide tolerance	Herbicide tolerance is the ability of a plant to be less affected by a dose of herbicide than the wild type plant, although the growth and fertility may be reduced. It is often used interchangeably with herbicide resistance.
Hybridize	To produce offspring of two animals or plants of different races, breeds, varieties, species, or genera.
Imidazoline	A group of herbicides which inihibit the enzyme acetolactate synthase (ALS) – in group B of the Australian classification of herbicides by mode of action, see Appendix 1. They include Arsenal, and Spinnaker,.
Immunological	Relating to the immune system, which functions to protect us from invasion by micro-organisms.
Introgression	Backcrossing of hybrids of two plant populations to introduce new genes into a wild population.
Ioxynil	Herbicides which inhibit photosynthesis at photosystem II. They are in group C of the Australian classification of herbicides by mode of action (see Appendix 1) and include Totril, and Unyunox Selective,.
Leaching	The removal of substances from soil through the action of water.
Lectins	Proteins which specifically bind (or crosslink) carbohydrates, often agglutinating (clumping) cells. Their physiological functions is unclear.
Maternally	Through the mother.
Metabolites	The products of metabolism, that is, the remains of a pesticide after living organisms in the environment have had their effects.
Microinjection	A technique for introducing a solution of DNA, protein or other soluble material into a cell using an extremely fine instrument.
Monocotyledons	A subclass of plants based on anatomical characteristics. They tend to have narrow leaves, a single seed leaf, parallel veins in the leaves, flower parts are usually in multiples of threes, a scattered arrangement of primary vascular bundles in the stem and a fibrous root system.
Mutation	A relatively permanent change in genetic material which can be passed on to the following generations.

Mutated	Genetic material which has had a mutation induced.
Neurotoxins	Poisons which act on the nervous system.
Nucleotides	A subunit of DNA or RNA consisting of a nitrogenous base (adenine, guanine, thymine, or cytosine in DNA; adenine, guanine, uracil, or cytosine in RNA), a phosphate molecule, and a sugar molecule (deoxyribose in DNA and ribose in RNA). Thousands of nucleotides are linked to form a DNA or RNA molecule.
Outcrossing	Many crop species self-pollinate but pollen can spread by wind or insects to nearby plants and, if the plants are compatible, the pollen can fertilise female plants. This is known as outcrossing.
Paraquat	A herbicide which inhibits photosynthesis at photosystem I (in group L of the Australian classification of herbicides by mode of action, see Appendix 1). Australian herbicides include Gramoxone, and Uniquat,.
Pesticide	A chemical used to kill pests, including weeds and insect pests.
Photosynthesis	Process through which light energy, water and carbon dioxide are converted to carbohydrate and oxygen. It occurs in plants, algae, cyanobacteria and lichens.
Photosystems I and II	Parts of the process of photosynthesis when energy from light is used by the plants.
Phytotoxic	Poisonous to plants.
Plasma membrane	The membrane that contains a cell's contents, separating it from the environment. It consists of a double layer of phospholipids and has proteins embedded in it.
Plasmid	Autonomously replicating, extrachromosomal circular DNA molecules which are separate from the normal bacterial genome and are not usually essential for cell survival. Some plasmids are capable of integrating into the host genome. A number of artificially constructed plasmids are used in biotechnology.
Post emergence	Used or occurring in the stage between the emergence of a seedling and the maturity of a crop plant
Progeny	Offspring or descendants.
Prophylactic	Preventative, for example, applying herbicide to stop weeds developing.
Propagules	Parts of a plant, such as a cutting, a seed, or a spore which can develop into a new plant.

Protease	An enzyme that breaks down protein molecules by cutting the bonds that link the amino acids in the protein.
Protoplasts	Plant cells which have had the cell wall removed so that DNA can be inserted.
Selective herbicides	Herbicides which are effective on only some plant types, for example effective against broadleaf weeds but not against grasses.
Sulfonylurea	A group of herbicides which inhibit the enzyme acetolactate synthase (ALS). They are in group B of the Australian classification of herbicides by mode of action (see Appendix 1). Australian examples are Ally, and Logran,.
Thinning	Reducing the number of plants in an area, either by physically removing them or by killing some of them.
Toxin	Poison - any of various organic poisons produced in living or dead organisms.
Transformed cell	A cell that has been genetically altered through the uptake of foreign genetic material.
Transgenic	An animal or plant whose genome has been altered by the transfer of a gene or genes from another species or breed.
Triazine	A group of herbicides which inhibitors of photosynthesis at photosystem II. They are in group C of the Australian classification of herbicides by mode of action (see Appendix 1). Australian examples are Bladex’, Gesagard’, Gesaprim’ and Igran’.
Vancomycin	An antibiotic used to treat infections, including enterococci infections in people.

Abbreviations

2,4-D	The herbicide 2,4-dichlorophenoxy acetic acid
AFFA	Department of Agriculture, Fisheries and Forestry – Australia
ANZFA	Australia New Zealand Food Authority (Now called FSANZ)
ANZFSC	Australia New Zealand Food Standards Council
AQIS	Australian Quarantine and Inspection Service
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
AVCPC	Agricultural and Veterinary Chemical Policy Committee
BRS	Bureau of Rural Sciences
Bt	*Bacillus thuringiensis*, a bacterium which contains insecticidal proteins used in genetically modified crops.
CSIRO	Commonwealth Scientific Industrial Research Organisation
DNA	deoxyribonucleic acid
EPA	Environmental Protection Agency
FSANZ	Food Standards Australia New Zealand (formerly ANZFA)
GATS	General Agreement on Trade in Services
GATT	General Agreement on Tariffs and Trade
GM	genetically modified
GMO	genetically modified organism
GTCAC	Gene Technology Community Consultative Committee
GTEC	Gene Technology Ethics Committee
GTR	Gene Technology Regulator
GTRAP	Gene Therapy Research Advisory Panel
GTTAC	Gene Technology Technical Advisory Committee
imi	imidazolinone herbicides
IOGTR	Interim Office of the Gene Technology Regulator
NICNAS	National Industrial Chemicals Notification and Assessment Scheme
NRA	National Registration Authority for Agricultural and Veterinary Chemicals

OGTR	Office of the Gene Technology Regulator
RNA	Ribonucleic acid
TGA	Therapeutic Goods Administration
TT canola	triazine-tolerant canola
UK	United Kingdom
USDA	United States Department of Agriculture
WTO	World Trade Organization

APPENDIX 1 : Australian classification of herbicides by mode of action

GROUP A: INHIBITORS OF FAT (LIPID) SYNTHESIS BY INHIBITING ACETYL COA CARBOXYLASE (ACCASE)

- **Arlyoxyphenoxypropionates ('FOPS'):** Correct®, Falcon®, Fusilade®, Hoegrass®, Puma S®, Shogun®, Targa®, Topik®, Tristar®, Verdict®, Wildcat®, diclofop
- **Cyclohexanediones ('DIMS'):** Achieve®, Fusion®, Select® , Sertin®, Sertin® Plus

GROUP B: INHIBITORS OF ACETOLACATE SYNTHASE (ALS), ALSO KNOWN AS ACETOHYDROXY ACID SYNTHASE (AHAS)

- **Sulfonylureas:** Ally®, Brush-Off®, Cut-Out™, Glean®, Harmony®M, Logran®, Londax®, Monza®, Oust®, Renovate®, Titus®, metsulfuron, chlorsulfuron
- **Imidazolinones:** Arsenal®, Flame®, OnDuty®, Spinnaker®
- **Sulfonamides:** Broadstrike®, Eclipse®

GROUP C: INHIBITORS OF PHOTOSYNTHESIS AT PHOTOSYSTEM II

- **Triazines:** Agtryne® MA (also contains MCPA – a group I herbicide), Bladex®, Gesagard®, Gesaprim®, Igran®, atrazine, simazine, terbutryn
- **Triazinones:** Lexone®, Sencor®, Velpar®, metribuzin
- **Ureas:** Afalon®, Cotoran®, Graslan®, Karmex®, Tribunil®, Probe®, Tupersan®, Ustilan®, diuron, linuron
- **Nitriles:** Buctril®200, Buctril®MA (also contains MCPA – a group I herbicide), Jaguar® (also contains diflufenican – a group F herbicide), Totril®, bromoxynil
- **Benzothiadiazoles:** Basagran®
- **Acetamides:** Ronacil®
- **Uracils:** Hyvar®, Krovar®, Sinbar®
- **Pyridazinones:** Pyramin®
- **Phenyl-pyridazines:** Tough®

GROUP D: INHIBITORS OF TUBULIN FORMATION

- **Dinitroanilines:** Relay®, Surflan®, Stomp®, Treflan®, Yield®, trifluralin
- **Benzoic acids:** Chlorthal®
- **Pyridines:** Visor®

GROUP E: INHIBITORS OF MITOSIS

- **Thiocarbamates:** Avadex®BW, Eptam®, Ordam®, Saturn®, Tillam®, Vernam®, molinate
- **Carbamates:** chloropropham
- **Organophosphorous:** bensulide

GROUP F: INHIBITORS OF CARETENOID BIOSYNTHESIS

- **Nicotinanilides:** Brodal®, Jaguar® (also contains bromoxynil – a group C herbicide), Tigrex® (also contains MCPA – a group I herbicide)
- **Triazoles:** amitrole
- **Pyridazinones:** Solicam®
- **Isoxazolidinones:** Command®, Magister®
- **Pyrazoles:** Taipan®

GROUP G: INHIBITORS OF PROTOPORPHYRINOGEN OXIDASE

- **Diphenyl ethers:** Affinity®, Blazer®, Goal®, Spark™
- **Oxadiazoles:** Ronstar®

GROUP I: DISRUPTORS OF PLANT CELL GROWTH

- **Phenoxys:** 2,4-D, 2,4-DB, MCPA, Barrel® (also contains bromoxynil – a group C herbicide and dicamba – a group I herbicide), Buctril®MA (also contains bromoxynil – a group C herbicide), Tigrex® (also contains diflufenican – a group F herbicide), Tillmaster® (also contains glyphosate – a group M herbicide)
- **Benzoic acids:** Banvel®, Cadence®, dicamba
- **Pyridines:** Garlon DS®, Lontrel®, Tordon® 242, Tordon® 75-D, Starane®, triclopyr

GROUP J: INHIBITORS OF CELL WALL SYNTHESIS

- **Alkanoic acid:** Propon

GROUP K: HERBICIDES WITH MULTIPLE SITES OF ACTION

- **Amides:** Devrinol®, Dual Gold®, Enide®, Kerb®WP, Ramrod®, napropamide, metolachlor
- **Carbamates:** Asulox®, Betanal®, Carbetamex®,asulam
- **Amino propionates:** Mataven L ®
- **Benzofurans:** Tramat®, ethofumesate
- **Phthalamates:** Alanap®
- **Nitriles:** dichlobenil

Group L: Disruptors of photosynthesis at photosystem I

- **Bipyridyls:** Gramoxone®, Reglone®, Spray.Seed®, paraquat, diquat,

GROUP M: INHIBITORS OF THE ENZYME 5-ENOLPYRUVYLSHIKIMATE-3-PHOSPHATE SYNTHASE (EPSPS)

- **Glycines**: Roundup®, Tillmaster® (also contains 2,4-D – a group I herbicide), Touchdown, glyphosate

GROUP N: INHIBITORS OF GLUTAMINE SYNTHETASE

- **Glycines:** Basta®, glufosinate ammonium, phosphinothricin

Source: Avcare 2000, Thomas 1997, Chris Preston (pers comm.)

APPENDIX 2 : Herbicide resistance for transgenic crops

Different genes are incorporated into crops to produce resistance to the different herbicides. For some herbicides, several genes have been idenitifed which can provide resistance, which means some options are available when producing crops resistant to that herbicide. Most effort has been put into developing crops resistant to the non-selective herbicides glyphosate and glufosinate ammonium.

Glyphosate resistance

Glyphosate inhibits the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), the sixth in the shikimic acid pathway leading to the aromatic amino acids tryptophan, tyrosine and phenylalanine (Steinrucken and Amrhein 1980). Glyphosate tolerant bacteria and plant cell cultures have been found, with at least two different mechanisms of overcoming the herbicide. In a glyphosate tolerant petunia cell line, an increased amount of EPSPS was found (Shah *et al.* 1985), which was also true for some bacteria such as *E. coli*. This was found to be due to an increased number of copies of the EPSPS gene (Shah *et al.* 1986). Introducing the petunia gene to tobacco, along with a strong promoter caused the tobacco to have elevated levels of EPSPS and to be tolerant to glyphosate (Shah *et al.* 1986).

In some glyphosate resistant strains of the bacteria *Aerobacter aerogenes* and *Salmonella typhimurium*, the EPSPS gene (*Aro*A) was found to be insensitive to glyphosate (for example, Comai *et al.* 1985). The *Aro*A gene has been cloned from *Salmonella typhimurium* and inserted into tobacco and tomatoes (Comai *et al.* 1985). These transgenic plants were only partially protected against glyphosate. Better protection was achieved by using an *Escherichia coli* EPSPS gene and coupling it to another gene to ensure the protein was correctly processed and transported in the host plant (della Cioppa *et al.* 1987). Recent trials of herbicide tolerant canola have incorporated the EPSPS gene from *Agrobacterium* var CP4. The EPSPS enzyme produced is resistant to glyphosate (Chris Preston, personal communication).

The third approach of introducing genes for proteins which degrade glyphosate. The gene is from *Achromobacter* (a bacterium) and encodes an enzyme (glyphosate oxidoreductase) which converts glyphosate to non-herbicidal chemicals (aminomethylphosphonic acid and glyoxylate) (Duke 1996).

In Australian field trials, the first method of overproducing the target site has been used alone in cotton (PR-55), with insecticidal genes in cotton (PR-81, PR-83, PR-94, PR-109) and in conjunction with the third approach of inactivating the herbicide in cotton (PR-32, PR-52, PR-71) (Genetic Manipulation Advisory Committee 2000).

Glufosinate ammonium tolerance

Resistance to glufosinate ammonium (an inhibitor of the enzyme glutamine synthetase) has been achieved by introducing a bacterial gene which codes for an enzyme, phosphinothricin acetyl transferase, which inactivates the herbicide by acetylation. The gene (*bar*) was isolated from a *Streptomyces hygroscopicus* strain (de Block *et al.* 1987, Thompson *et al.* 1987). Glufosinate resistance has also been found to be a convenient marker to select for transgenic crops in tissue culture and field trials and has therefore been used in trials where other traits are being developed. The *bar* gene has been inserted into numerous crop species trialled in Australia, including barley (PR-88, PR-92, PR-106), canola (PR-62, PR-63, PR-79, PR-85, PR-93), cotton (PR-82), Indian mustard (PR-90), lupins (PR-40, PR-49, PR-74, PR-75, PR-76), peas (PR-59, PR-61, PR-80, PR-96), poppies (PR-103), subterranean clover (PR-37) and wheat (PR-65, PR-102, PR-107) (Genetic Manipulation Advisory Committee 2000).

Another method of producing resistance to glufosinate is to overproduce the enzyme glutamine synthetase. This has been done to produce transgenic tobacco resistant to glufosinate (Eckes *et al.* 1987).

Bromoxynil tolerance

Bromoxynil, a potent inhibitor of photosynthetic electron transport at the photosystem II site, also acts as an uncoupler of oxidative and photosynthetic phosphorylation (Fedtke 1982). A gene that detoxifies bromoxynil (*bxn* gene) was identified, isolated and cloned from a plasmid in the bacteria *Klebsiella ozaneae* (Stalker and McBride 1987, Stalker *et al.* 1988a, 1988b). The gene codes for nitrilase, an enzyme that breaks down the herbicide bromoxynil into the primary metabolite (3,5-dibromo-4-hydroxybenzoic acid) which is at least 100-fold less toxic to plant cells than bromoxynil. The nitrilase gene has also been isolated from the soil bacterium *Klebsiella pneumoniae*. Transgenic subterranean clover (PR-58) and cotton (PR-69) which are resistant to bromoxynil have been trialled in Australia. They were produced by adding the nitrilase gene from *Klebsiella pneumoniae* (Genetic Manipulation Advisory Committee 2000).

Tolerance to acetolactate synthase (ALS) inhibitors

Sulfonylureas and imidazolinone are narrow-spectrum herbicides that are effective at very low application rates. These herbicides inhibit the enzyme acetolactate synthase (ALS), also known as acetohydroxy acid synthase (AHAS), the first common enzyme in the biochemical pathway to the branched chain amino acids valine, leucine and isoleucine (Huppatz *et al.* 1995).

Herbicide tolerant crops have been developed for sulfonylureas and imidazolinones. The mechanism has been due to an ALS that is less sensitive to ALS inhibitors (Saari *et al.* 1994). Genes that code for a mutant ALS enzyme which differed from the wild type and were more resistant to sulfonylureas herbicides have been found in *Arabidopsis thaliana* (*csr1-1* gene), tobacco (*SurA* and *SurB* genes) and canola (*ahas3r* gene) (Saari and Mauvais 1996). Another gene (*csr 1-2*) was isolated from a mutant

Arabidopsis thaliana which resulted in tolerance to imidazolinones but not to sulfonylurea (Shaner *et al.* 1996). Mourad *et al.* (1994) also developed *Arabidopsis thaliana* plants with resistance to both sulfonylureas and imidazolines by producing and selecting double mutant constructs (*csr 1-4*) containing the *csr 1-1* and *csr 1-2* mutations.

A chlorsulforon tolerance gene has been taken from tobacco and inserted into carnations released in Australia (PR- 28, PR-29, PR-298/29X, PR-84, GR-1, GR-2), roses (PR-35) and resistance to chlorsulforon used as a marker in transgenic pineapple development in Australia (PR-95, Genetic Manipulation Advisory Committee 2000).

Tolerance to 2,4-D

A number of soil bacteria have been found to degrade 2,4-D, including *Pseudomonas*, *Arthrobacter*, *Acinetobacter* and *Alcaligenes*. The genes from *Alcaligenes eutrophus* have been characterised, and the first gene in the pathway , the *tfdA* gene codes a 2,4-D degrading monooxygenase (Lyon *et al.* 1989, Huppatz *et al.* 1995). This gene has been introduced into cotton in Australian field trials, to protect the cotton from 2,4-D spray drift (PR-54, Genetic Manipulation Advisory Committee 2000).

APPENDIX 3 : Australian herbicide resistant weeds

Genus and Species	Common Name	States	Herbicide Group	Herbicides
Arctotheca calendula	Capeweed	Vic	L	Paraquat, diquat
Avena fatua	Wild oats	SA NSW Vic WA Qld	A	Diclofop-methyl, fenoxaprop-p-ethyl, clodinafop-propargyl, haloxyfop-ethoxyethyl, quizalofop-p-ethyl, fluazifop-p-butyl, tralkoxydim
Avena sterilis	Wild oats	SA NSW	A	Diclofop-methyl, fenoxaprop-p-ethyl, propaquizafop, haloxyfop-ethoxyethyl, quizalofop-p-ethyl, fluazifop-p-butyl, tralkoxydim
Brassica tournefortii	Wild turnip	SA WA	B	Chlorsulfuron, trisulfuron, metsulfuron-methyl, flumetsulam
Bromus diandrus	Brome grass	Vic	A	Haloxyfop-thoxytheyl, fluzifop-p-butyl, quizalofop-p-ethyl
Cyperus difformis	Dirty dora	NSW	B	Bensulfuron-methyl
Damasonium minus	Starfruit	NSW	B	Bensulfuron-methyl
Digitaria sanfuinalis	Large crabgrass	SA WA	A	Fluzifop-p-butyl, haloxyfop-ethoxyethyl, quizalofop-p-ethyl
	Large crabgrass	SA	B	Imazethapyr
Echium plantagineum	Paterson's curse	SA WA	B	Chlorsulfuron, triasulfuron, metsulfuron-methyl, sulfometuron-methyl
Fallopia convolvulus	Climbing buckwheat	Qld	B	Chlorosulfuron
Fumaria densiflora	Fumitory	NSW SA	D	Trifluralin
Hordeum leporinum	Barleygrass	SA	A	Quizalofop-p-ethyl, fluaxifop-p-butyl
	Barleygrass	Vic SA	L	Paraquat, diquat
Lactuca serriola	Prickly lettuce	SA	B	Chlorsulfuron, triasulfuron, metsulfuron-methyl, sulfometuron-methyl

Lolium rigidum	Annual ryegrass	SA Vic NSW WA	A	Diclofop-methyl, fluazifop-p-butyl, haloxyfop-ethoxyethyl, quizalofop-p-ethyl, tralkoxydim, sethoxydim, clethodin
	Annual ryegrass	SA Vic NSW WA	B	Chlorosulfuron, triasulfuron, sulfometuron-methyl, imazethapyr, imazapyr
	Annual ryegrass	SA Vic WA	C	Simaine, atrazine, diuron, metribuzin
	Annual ryegrass	SA WA	D	Trifluran, pendimethalin, oryzalin
	Annual ryegrass	SA WA	F	Amitrole
	Annual ryegrass	Vic NSW SA WA	M	Glyphosate
Phalaris paradoxa	Paradoxa grass	NSW	A	Fenoxaprop-p-ethyl, sethoxydim
Raphanus raphanistrum	Wild radish	WA SA	B	Chlorsulfuron, triasulfuron, metsulfruon-methyl, imazethapyr, flumetsulam, metosulam
	Wild radish	WA	C	Atrazine, simaine
	Wild radish	WA	F	Diflufenican, picolinofen
Rapistrum rugosum	Turnip weed	NSW	B	Chlorsulfuron
Sagittaria montevidensis	Arrowhead	NSW	B	Bensulfuron-methyl
Sinapis arvensis	Charlock	NSW	B	Cholorsulfuron
Sisymbrium orientale	Indian hedge mustard	NSW Qld SA WA	B	Chlorsulfuron, triasulfuron, metsulfuron-methyl, imazethapyr, metosulam, flumetsulam
Sisymbrium thellungii	African turnip weed	Qld	B	Chlorsulfuron
Sonchus oleraceus	Sowthistle	Qld NSW	B	Chlorsulfuron, triasulfuron, metsulfuron-methyl
Urochloa panicoides	Liverseed grass	Qld	C	Atrazine
Vulpia bromoides	Silvergrass	Vic	L	Paraquat, diquat

Chris Preston - personal communication