Herbicide resistance – Australia vs. the rest of the world

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Summary There are currently 38 documented herbicide resistant weed biotypes in Australia, more resistant weeds than any other country except the USA. Multiple resistant *Lolium rigidum* is Australia's and the world's worst case of herbicide resistance, infesting more than a million hectares of the Australian cereal belt and exhibiting resistance to up to eight different herbicide modes of action. Whilst multiple-resistance in *Lolium rigidum* has had a severe economic impact on the Australian farmer it has also been a driving force behind innovative herbicide resistance research and integrated weed management. ALS and ACCase inhibitor herbicides account for the greatest increases in new herbicide resistance cases both in Australia and worldwide. The recent introduction of herbicide resistant crops provide additional herbicide modes of action for control of *Lolium rigidum* however difficulties in getting farmers to adopt proactive resistance management strategies may eventually lead to the widespread occurrence of glyphosate resistant *Lolium rigidum* throughout the cereal belt of Australia.
Keywords Herbicide resistance, *Lolium rigidum*, cross-resistance, multiple resistance, mode of action, ACCase inhibitors, ALS inhibitors, glyphosate.

INTRODUCTION

In the developed world, and increasingly worldwide, herbicides are the primary method of weed control and their effectiveness is largely responsible for the current abundance of food globally (Avery 1995). Herbicides have become the primary method of weed control because of their efficacy and cost effectiveness however heavy reliance on herbicides has resulted in the widespread occurrence of herbicide-resistant weeds. Herbicide resistance continues to increase globally causing significant yield losses and increasing the cost of food production. Australia is not only a source of the most serious case of herbicide resistance globally, but is also a world leader in innovative solutions to mange herbicide resistance. This paper will outline some of the similarities and differences between herbicide resistance in Australia and the rest of the world.

HERBICIDE RESISTANCE

As the introductory paper to this symposium on herbicide resistance I will give a brief definition of resistance and its causes in weeds.

Herbicide resistance is the evolved capacity of a previously herbicide susceptible weed population to withstand a herbicide and complete its life cycle when the herbicide is used at its normal rate in an agricultural situation (Heap and Lebaron 2001).

'Evolved capacity' in this definition implies that resistance is caused by a heritable change (mutation) in the genetic makeup of the weed that confers to it the ability to withstand a herbicide. Most herbicides act by inhibiting a specific enzyme (different for different herbicide modes of action) within the plant (Devine *et al.* 1993). The majority of herbicide resistance cases are due to the selection of rare individuals with genes that code for a modification of the target enzyme such that the herbicide no longer binds to or inhibits the enzyme. Classic examples of this are commonly found in ACCase inhibitor, ALS inhibitor, dinitroaniline, EPSPS and triazine resistant weeds. Over expression of the target enzyme can also result in resistance.

In addition to altered target sites, weeds may evolve resistance due to the exclusion of herbicides from the site of action (reduced absorption, reduced translocation, or sequestration), or by rapid detoxification of herbicides. It is this final mechanism, rapid detoxification conferred by elevated cytochrome P450 monooxygenase activity, that often results in resistance to a wide array of chemical modes of action and indeed is one of the mechanisms found in *Lolium rigidum* Gaudin. (Christopher *et al.* 1991, Cotterman *et al.* 1992)

To add to the complexity of resistance there are many instances where more than one resistance mechanism is found in a population (multiple resistance), and often within the same individual. The most complex examples are those of multiple resistant *Lolium rigidum* (Heap and Knight 1982, Heap and Knight 1986, Holtum and Powles 1991, Hall 1994) from Australia, and *Alopecurus myosuroides* Huds. (Moss and Cussans 1991, Hall 1994, Sharples and Cobb 1996) from Europe, where rapid detoxification and a number of target site resistances often occur in the same population, making research into the mechanisms of resistance difficult, and advice to the farmers about effective alternatives even more difficult (Willis *et al.* 1997).

OCCURRENCE OF RESISTANCE

A few reports of weeds exhibiting reduced (<5 fold) levels of control with 2,4-D in the 1950s did not receive much attention by farmers or scientists. The discovery of simazine resistant *Senecio vulgaris* L. populations in a Washington state nursery (USA) in the late 1960s (Ryan 1970) is commonly cited as the first case of herbicide resistance. This case received a great deal of attention because it had major implications for triazine dependent maize producers in the USA and Europe, and indeed over thirty triazine resistant weed species were identified in maize by the end of the 1970s. Triazine resistant weeds were extensively researched but did not inflict as much economic damage to producers as first feared because alternative herbicide modes of action had arrived to market in time to avoid serious weed control problems.

Australia vs. the World In May 2002 the International Survey of Herbicide-Resistant Weeds recorded 258 herbicide-resistant weed biotypes in 53 countries (Heap 2002). Australia appears to have a disproportionately high number of herbicide resistant weeds, having documented 38 resistant weed biotypes in 25 species, second only to the USA (Tables 1 and 2).

A new resistant biotype refers to the first instance of a weed species evolving resistance to one or more herbicides in a herbicide group. It is worth noting that *Lolium rigidum* has been identified with resistance to eight different herbicide modes of action and thus accounts for eight of the 38 resistant biotypes. There are several other species in Australia with resistance to more than one herbicide group (Table 2).

The rate of identification of new herbicide resistance cases is surprisingly constant for both the global and Australian data. Worldwide there have been approximately nine new cases of resistance per year since 1980 and in the same time period Australia has added about two new cases each year (Figure 1).

Table 1. The number of herbicide resistant biotypes reported by country for the top ten countries.

Country	Resistant biotypes
USA	88
Australia	38
Canada	36
France	30
Spain	24
United Kingdom	23
Israel	19
Belgium	18
Germany	17
Japan	14

ALS and ACCase inhibitors account for the greatest increases in new resistance cases worldwide and in Australia (Figures 2 and 3). There are 72 ALS inhibitor resistant weed species worldwide, and 15 of these occur in Australia. The majority of the Australian cases are broadleaf weed species in cereal crops (Table 2) whilst globally ALS resistant weeds are found in all major crops. Of the 28 grass species resistant to ACCase inhibitors eight can be found in Australia, again primarily in cereal crops (Heap 2002).

It is not surprising that the proportion of triazine resistant weeds found in Australia is lower than in the global statistics, as triazines have not been widely used in Australia. However with the recent increase in triazine tolerant Canola, used for control of herbicide resistant *Lolium rigidum*, the incidence of triazine resistant weeds in Australia is likely to increase.

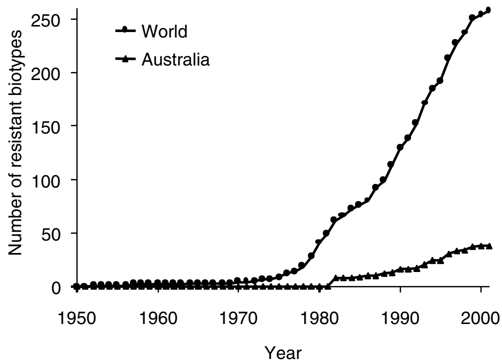

Figure 1. The chronological increase in the number of herbicide-resistant weeds in Australia and worldwide.

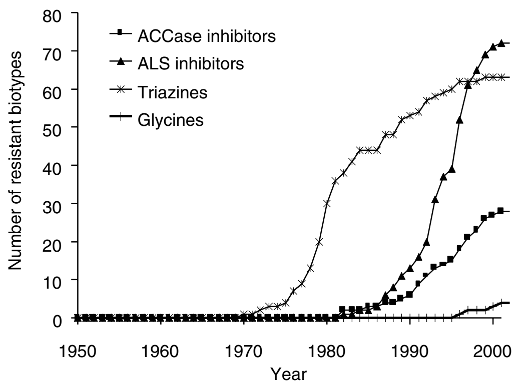

Figure 2. The chronological increase in the number of herbicide-resistant weeds in worldwide to four herbicide classes.

Table 2. The occurrence of herbicide resistant weeds in Australia.

#	Species	Common Name	First Year	Herbicide Mode of Action (State:Year)
1	*Arctotheca calendula* L.	Capeweed	1986	Bipyridiliums (Vic:96)
2	*Avena fatua* L.	Wild oat	1985	ACCase inhibitors (WA:85, SA:88, NSW:91)
3	*Avena sterilis* L.	Wild oat (sterile)	1989	ACCase inhibitors (NSW:89, SA:89)
4	*Brassica tournefortii* Gouan.	Wild turnip	1992	ALS inhibitors (WA:92)
5	*Bromus diandrus* Roth.	Great brome	1999	ACCase inhibitors (Vic:99)
6	*Cyperus difformis* L.	Smallflower umbrella sedge	1994	ALS inhibitors (NSW:94)
7	*Damasonium minus* (R.Br.) Buch.	Starfruit	1994	ALS inhibitors (NSW:94)
8	*Digitaria sanguinalis* L.	Large crabgrass	1993	*(ACCase inhibitors and ALS inhibitors) (SA:93)
9	*Echium plantagineum* L.	Salvation Jane	1997	ALS inhibitors (WA:97, SA:97)
10	*Fallopia convolvulus* (L.) A. Love	Climbing buckwheat	1993	ALS inhibitors (QLD:93)
11	*Fumaria densiflora* DC.	Dense-flowered fumitory	1999	Dinitroanilines (NSW:99)
12	*Hordeum glaucum* Steud.	Wall barley	1984	Bipyridiliums (Vic:84, SA:96), ACCase inhibitors (SA:2000)
13	*Hordeum leporinum* Link	Barley grass	1988	Bipyridiliums (Vic:88), ACCase inhibitors (SA:96, NSW:2001)
14	*Lactuca serriola* L.	Prickly lettuce	1994	ALS inhibitors (SA:94)
15	*Lolium rigidum* Gaudin	Annual ryegrass	1982	*(ACCase inhibitors, ALS inhibitors, Dinitroanailines, and 5 other MOA's) (SA:82, WA:82, VIC:84, NSW:85), Glycines (Vic:96, NSW:97, WA:01)
16	*Phalaris paradoxa* L.	Paradoxa grass	1997	ACCase inhibitors (NSW:97)
17	*Raphanus raphanistrum* L.	Wild radish	1997	ALS inhibitors (WA:97, SA:98), *(ALS and Carotenoid biosynthesis inhibitors) (WA:98), Photosystem II inhibitors (WA:99)
18	*Rapistrum rugosum* L.	Turnipweed	1996	ALS inhibitors (QLD:96)
19	*Sagittaria montevidensis* Cham. & Schlecht.	California arrowhead	1994	ALS inhibitors (NSW:94)
20	*Sinapis arvensis* L.	Wild mustard	1996	ALS inhibitors (NSW:96)
21	*Sisymbrium orientale* L.	Indian hedge mustard	1990	ALS inhibitors (SA:90, QLD:93, NSW: 94,WA:94)
22	*Sisymbrium thellungii* L.	African turnip weed	1996	ALS inhibitors (QLD:96)
23	*Sonchus oleraceus* L.	Sowthistle	1990	ALS inhibitors (QLD:90)
24	*Urochloa panicoides* Beauv.	Liverseedgrass	1996	Photosystem II inhibitors (QLD:96)
25	*Vulpia bromoides* (L.) S.F.Gray	Silvergrass	1990	Bipyridiliums (Vic:90)

*(Multiple resistance) – note: not all populations have resistance to all herbicide groups stated.

The cases of glyphosate resistant *Lolium rigidum* in Australia, and cases of glyphosate resistance in three other species (*Lolium multiflorum* L., *Eleusine indica* (L.) Gaertn., and *Conyza Canadensis* (L.) Cronq.) in other countries have major implications for the management of glyphosate resistant crops globally. While it is clear that glyphosate is a low risk herbicide for selection of resistant weeds these cases have made it equally clear that glyphosate resistant weeds will appear given sufficient selection pressure and time.

The graphs and data presented in this paper are summaries of the International Survey of Herbicide-Resistant Weeds and can be found on the web (http://www.weedscience.com).

World's worst resistant weed Multiple resistant *Lolium rigidum* is Australia's and the world's worst case of herbicide resistance. It is estimated that over a million hectares of the Australian cereal belt are infested with herbicide resistant *Lolium rigidum* (Heap 2002). Whilst many of these resistant populations have target site resistance to ALS inhibitors and/or ACCase inhibitors, there are sufficient that have multiple resistance, including non-target site resistance, to complicate the normal advice of using an alternative herbicide mode of action. Some populations have been identified with resistance to eight herbicide modes of action (Holtum and Powles, 1991). Why did *Lolium rigidum* become the worst herbicide resistant weed in the world? *Lolium rigidum* is very well adapted to the

Mediterranean climate of the Australian wheat belt and has been a desirable pasture species for much of last century which has led to it being very widespread and abundant. Being widespread, abundant, and clearly detrimental to cereal yields made it a prime target for herbicides but this alone does not explain the rapid evolution of herbicide resistance in ryegrass, as there are many species around the world that fit this description. Biological factors of this species converge to make it the ideal candidate for the evolution of herbicide resistance. It is genetically diverse, outcrossing, it produces masses of seed and the seed has low seed dormancy, all factors that drive rapid evolutionary changes and have contributed to the creation of the worst herbicide resistant weed in the world.

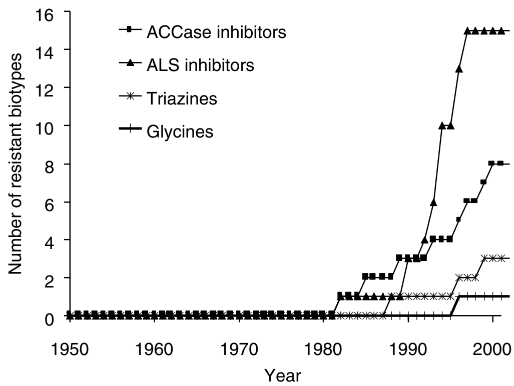

Figure 3. The chronological increase in the number of herbicide-resistant weeds in Australia to four herbicide classes.

RESISTANCE MANAGEMENT STRATEGIES

Australia leads the world in seeking novel cultural controls to solve herbicide resistance problems. In North America and Europe the primary focus has been the use of herbicide rotations, mixtures, or sequences that involve different herbicide modes of action. Multiple resistant *Lolium rigidum* in Australia has necessitated an integrated weed management approach that has a strong component of non-chemical controls (Matthews and Powles 1996, Gill and Holmes 1997). Common resistance management strategies that are been used (to varying degrees) by farmers around the world are listed below.

Herbicide rotation Rotating between herbicide modes of action from year to year is the most widespread and probably most cost effective method of resistance management.

Herbicide mixtures or sequences In this strategy different herbicide modes of action are used at full rates to control the same weed species, thus making the probability of target site resistance extremely low as the same individual would require a mutation to both herbicide modes of action. Expense is usually the major deterrent to using mixtures or sequences, particularly with sequences as they require additional applications. Care must be taken to choose herbicides that will not select for metabolism based resistance to both modes of action.

Cultural/Non-chemical control Strategies that include non-chemical control are often suggested in resistance management but rarely adopted unless they provide immediate economic benefit to the farmer – usually this happens after the appearance of resistance. Most strategies are aimed at reducing seed production or the seed bank prior to cropping. They include crop rotation, stubble burning, cultivation to stimulate weed germination, delayed sowing to maximise pre-sowing weed kill, spray-topping, crop-topping, hay cutting, and capture of weed seed during harvest (Mathews and Powles 1996). Establishment of a highly competitive crop is probably the best example of a cultural control that provides immediate economic benefits.

ADOPTION OF RESISTANCE MANAGEMENT

Over the last 30 years scientists have studied the mechanisms of herbicide resistance, cross-resistance patterns, distribution of resistance, genetics, gene flow, biology, and ecology of resistance. All of these studies are necessary for an understanding of herbicide resistance and are useful in the development of resistance management strategies. Often the devised strategies are extended to farmers via fact sheets, work shops and the popular press. Unfortunately the weak link in the chain is the adoption of resistance management strategies by farmers. Whilst the research and development arm of industry has been proactive in supporting herbicide resistance research, and the development of resistance management strategies, the sales and marketing arm of industry often ignores this advice and promotes repeated use of the same product year after year.

In addition there is a common (and so far relatively accurate) perception by farmers that by the time they have a resistance problem industry will provide a new herbicide that will effectively solve the problem, thus making proactive and expensive resistance management strategies unnecessary. This is a dangerous assumption as the economic consequences are severe if/when industry is unable to provide the next solution in time.

Glyphosate may be the most important herbicide resource that Australian farmers have left and the introduction of Roundup Ready crops provides farmers with a useful tool for controlling existing resistant weeds. However unless carefully managed, Roundup Ready crops in Australia are not likely to be a long term silver bullet. Widespread resistance of *Lolium rigidum* to glyphosate will take considerably longer than it took for widespread resistance to ALS or ACCase inhibitor herbicides, but complete reliance on glyphosate for ryegrass control both pre-plant and post-emergence will probably spell the beginning of its demise within a decade.

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