HERBICIDE RESISTANCE IN WEEDS OF SOUTHERN AUSTRALIA: WHY ARE WE THE WORST IN THE WORLD?

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Abstract Herbicide resistance in weeds is widespread across the southern Australian cropping region. Currently, populations of 22 weed species are resistant to herbicides from seven different modes of action. The reasons for the large number of fields with herbicide resistant weeds in southern Australia involve: continuous cropping systems highly dependent on herbicides for weed control; the high population densities of weeds, particularly Lolium rigidum Gaudin, that infest cropping fields; and the widespread use of the Group A (acetyl-coenzyme A carboxylase inhibitors) and Group B (acetolactate synthase inhibitors) herbicides for weed management across much of southern Australia. The introduction of herbicide-tolerant crop varieties will change the use patterns of a number of herbicides in Australia. An analysis of such crop and herbicide packages suggests that, for some, there is the distinct danger of greatly increased selection pressure for herbicide resistance. Many herbicide-tolerant crop varieties may prove extremely valuable weed management tools if used judiciously.

INTRODUCTION

The first herbicide-resistant weed population in Australia was reported in 1982 (Heap and Knight 1982). The numbers of weed species with resistant populations and the number of weed populations with resistance have both grown dramatically since then. Australia has one of the worst problems with herbicide resistant weeds in the world (Powles et al. 1997). While much of the problem occurs in southern Australian cereal cropping zones, other areas are not immune from resistance. Weed populations with resistance to herbicides occur in vegetable production, tree horticulture, rice culture, roadsides, railway lines, and from the northern cereal cropping zones (Burnet et al. 1991, Adkins et al. 1997, Powles et al. 1997, 1998). In this paper we look over the past 20 years of research on herbicide resistance in Australia to determine the major factors influencing the widespread appearance of resistance.

The recent and pending introductions of herbicide-tolerant crops provide farmers with additional herbicide tools for the control of weeds. However, are farmers across southern Australia going to learn from the past 20 years of history? Will these new crop cultivars prove a boon for agriculture or just be more of the same?

HERBICIDE RESISTANCE IN AUSTRALIA

The current situation Herbicide-resistant weed populations of 22 different weed species are present in Australia (Table 1). These resistant weed populations come from a number of different situations, but the vast majority of examples are from the winter cereal cropping zone of southern Australia. Typically, herbicide resistance has appeared in areas where one or a few herbicides were used persistently for the management of weeds.

The importance of weed numbers Lolium rigidum provides the greatest number of herbicide-resistant weed populations in Australia, followed by Avena fatua, A. sterilis ssp. ludoviciana, and Raphanus raphanistrum. These are also some of the most widespread weeds of cropping in Australia. When compared to other situations, a similar pattern emerges. For example, in the Canadian prairies A. fatua, and Setaria viridis (L.) P. Beauv. provide the bulk of examples of herbicide resistance and are also major weeds of cropping in that area (Morrison and Devine 1994).

L. rigidum, in particular, can occur in high numbers within cropping fields and is widespread across southern Australia (Gill, 1996). This species was actively encouraged in pasture phases resulting in large soil seed reserves. Therefore, large numbers of plants are sprayed with herbicide every year. The application of herbicides to large numbers of one species maximises the opportunities for selection of resistant types (Jasieniuk et al. 1996).
The importance of herbicide type

It is evident from Table 1 that the vast majority of examples of herbicide resistance in Australia are to herbicides from Groups A and B, with fewer examples of resistance to other herbicide groups. Experience suggests that fewer applications of Group B and A herbicides are needed before resistance is evident than for other herbicide groups (Table 2). The Group A and B herbicides are widely used for weed management in Australia; however, herbicide use patterns differ in other regions. Worldwide, the Group C herbicides are the most widely used followed by Group B and Group E herbicides.
(Powles et al. 1997); however, use of the Group B herbicides has increased greatly in the past few years. The incidence of herbicide resistance to the Group C and Group B herbicides reflects such worldwide usage patterns (Heap 1997).

Clearly, the size of the herbicide resistance problem in Australia is influenced by the extensive use of the more resistance prone Group A and B herbicides. In many cropping systems elsewhere in the world, more use is made of herbicides from Groups C and E. Resistance develops much more slowly to these herbicides.

Table 2. Average years of use of herbicides before the appearance of herbicide resistant weeds. Collated from Burnet et al. (1991), Purba (1993), Gill (1995), McAlister et al. (1995), and Powles et al. (1998). These values can vary depending on species and situation.

<table>
<thead>
<tr>
<th>Average years of use before resistance is evident</th>
<th>Herbicide groups</th>
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<tr>
<td>&lt;5</td>
<td>B</td>
</tr>
<tr>
<td>5-9</td>
<td>A</td>
</tr>
<tr>
<td>10-14</td>
<td>C, D, F</td>
</tr>
<tr>
<td>&gt;15</td>
<td>L, M</td>
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The importance of herbicide rates  There has been much speculation about how herbicide rates influence selection for resistance. The case has been made that resistance problems in southern Australia are, in part, caused by the lower herbicide rates used (Gressel et al. 1996, Gressel 1997). In part, the argument is that lower rates will allow the selection for polygenic resistance traits whereas higher rates select for stronger target-site based resistance mechanisms (Gressel et al. 1996).

Experience in Australia has demonstrated that target site-based resistance mechanisms are just as readily selected with low herbicide rates as with high rates. For example, many populations of L. rigidum in Western Australia resistant to sulfonylurea herbicides contained resistant target sites, despite low rates of herbicides being used (Gill 1995).

Low rates will allow expression of weaker resistance mechanisms that will not appear if higher rates are used. However, these can be weak target site mechanisms as easily as metabolism-based mechanisms. For example, some populations of A. sterilis ssp. ludoviciana resistant to Group A herbicides have an acetyl-coenzyme A carboxylase with only 3 to 4-fold resistance to diclofop acid (Maneechote 1995). L. rigidum populations containing a weak resistance mechanism may also have a second, stronger resistance mechanism. The weaker mechanism may be enhanced metabolism or a target site modification (Preston et al. 1996, Preston and Powles 1998). Overall, low herbicide rates seem unlikely to have been a significant cause of the evolution of herbicide resistance in Australia (Preston and Roush 1998).

What can be learnt from past history?  Herbicide resistance is most likely to occur if herbicides are used intensively against large populations of weeds. Resistance will appear faster with some modes of action compared to others. With L. rigidum, in particular, large populations have been persistently treated with herbicides from Groups A and B. The net result has been large numbers of L. rigidum populations with herbicide resistance.

HERBICIDE TOLERANT CROPS

Types of crops  Herbicide-tolerant crops, in the form of triazine-tolerant canola, are currently grown in southern Australian cropping systems. In the next few years, crop cultivars expressing resistance to imidazolinone herbicides, glufosinate, glyphosate, bromoxynil, and probably other herbicides are likely to be released. The introduction of these herbicide-tolerant varieties will change use patterns of the herbicides involved and hence change the selection pressure for evolution of herbicide resistance.

The value of herbicide-tolerant crops can be realised in the management of hard to control weeds and of weed populations resistant to other herbicides (see Powles et al. 1997). However, it is important that lessons from history are heeded if the full value of herbicide-tolerant crops is to be realised.

Triazine tolerance  Triazine-tolerant canola is grown widely across southern Australia. Triazines are Group C herbicides and there are already weed populations with resistance to Group C herbicides in Australia (Table 1). Currently, triazines are used widely in pulse and lupin crops, particularly in Western Australia (Bowran 1996). The increased selection pressure offered by triazine use in triazine-tolerant canola has (S. Powles, unpublished data) and will exacerbate the development of herbicide resistance in areas with a previous history of intensive triazine herbicides use.

Bromoxynil tolerance  Bromoxynil is also a Group C herbicide, but from a different chemistry to the triazine herbicides discussed above. Triazine-resistant weed populations are not cross resistant to bromoxynil
if resistance is due to an altered target enzyme (Fuerst et al. 1986), or to glutathione-S-transferase-dependent detoxification mechanisms (Gray et al. 1995).

The introduction of bromoxynil-tolerant crops presents less of a concern than triazine-tolerant crops, due to the less widespread usage of bromoxynil. However, this does not extend to cropping systems where an intensive history of bromoxynil use exists. Evolved resistance to bromoxynil is rare (Heap 1997); however, this is probably a result of relatively low intensity use of this herbicide.

**Imidazolinone tolerance** The imidazolinones are Group B herbicides. There are large numbers of Group B-resistant weed populations in Australia (Table 1). Not all weed populations with Group B resistance have cross resistance to the imidazolinone herbicides; however, between 10 and 30% of sulfonylurea-resistant *L. rigidum* populations are cross resistant to imidazolinones (Gill 1995). Similar patterns of cross resistance are seen with Group B herbicide-resistant broadleaf weeds (C. Preston, unpublished data).

The introduction of imidazolinone-tolerant crops is likely to exacerbate the development of herbicide resistance, particularly in areas with a history of Group B herbicide use. The rapid development of resistance to Group B herbicides presents a significant challenge to the sustainable introduction of imidazolinone-tolerant crops.

**Glufosinate tolerance** Glufosinate is a Group N herbicide not currently registered for use in broad area crops in Australia. Therefore, the introduction of glufosinate-tolerant crops will represent the introduction of a new herbicide mode of action into southern Australian cropping. There are no examples of weed populations with evolved resistance to glufosinate (Heap 1997). Therefore, glufosinate is unlikely to be a herbicide at high risk of weeds developing resistance. If glufosinate-tolerant crops are used in a wide rotation, there is no reason to expect resistance to occur for some time.

**Glyphosate tolerance** Glyphosate is a Group M herbicide used extensively in agriculture and non-agricultural pursuits in Australia. Despite this widespread use, only recently have glyphosate-resistant weed populations been detected (Powles et al. 1998). Given the extensive use of glyphosate in southern Australia and the appearance of glyphosate-resistant *L. rigidum* populations, the introduction of glyphosate-tolerant crops might be seen as a high and unacceptable risk for future resistance problems.

The major current use for glyphosate in cropping situations is for pre-seeding weed control. Glyphosate is also used for reduction of grass weed seed set in pastures in the years prior to cropping. With the advent of glyphosate-tolerant crops, there will be post crop emergence use of this herbicide as well. Clearly, if post emergence glyphosate use is added to the existing uses, there is considerable risk for increased numbers of glyphosate-resistant weed populations. How then should the introduction of glyphosate-tolerant crops occur so as not to increase the risk for weed resistance? There are many possible strategies with the simplest being: the use of a herbicide other than glyphosate pre-seeding in years when glyphosate-tolerant crops are not grown; the use of an alternative to glyphosate pre-seeding when the glyphosate-tolerant crop is grown; or the use of a herbicide late in the season to stop seed set of survivors of glyphosate application.

**Simulation of resistance development** These scenarios were examined using a computer simulation program (Preston and Roush 1998), adapted to allow different levels of herbicide selection pressure in different years and to allow post herbicide weed control prior to weed seed set. The simulations assumed resistance to result from a single dominant gene. The model outcomes will be different if resistance is due to a recessive gene or multiple genes (Preston and Roush 1998); however, as the inheritance of glyphosate resistance in *L. rigidum* is unknown, it makes sense to err on the conservative side for the most difficult types of resistance to manage. The initial frequencies of resistance alleles for glyphosate are not known; however, as the rate of base-pair mutation is on average $10^{-9}$ (Jasieniuk et al. 1996); values between $10^{-8}$ and $10^{-9}$ were used. Seed survival over summer was set at 90% and seed remaining in the seed bank at 15% (Heap 1989). In years with pre-seeding glyphosate, the herbicide controls only the emerged fraction of the weed population. The percentage of whole season seedling emergence that occurs before crop sowing varies with season and locality, with values ranging from 69 to 90% reported (Heap 1989; Gramshaw and Stern 1977; McGowan 1970). An average of 77% was used for most simulations. It was assumed for the simulations that 95% of weeds emerging prior to sowing were controlled by the pre-seeding herbicide application and 95% of survivors and weeds emerging in crop were controlled by the in crop herbicide or other techniques.
The simulations predict that resistance will develop 7 or 8 years earlier with a glyphosate tolerant crop grown every 4th or 3rd year (Table 3). The simulations also predict a delay in glyphosate resistance by 2 to 3 years with use of a herbicide other than glyphosate pre-seeding either in the year the glyphosate-tolerant crop is grown or in a year after the glyphosate-tolerant crop is grown. A delay in the appearance of resistance of between 4 and 6 years occurs with use of herbicides other than glyphosate pre-seeding for 2 years after the glyphosate-tolerant crop.

Table 3. Predicted evolution of resistance to glyphosate (years for resistant allele to reach a frequency of 50%) for several use patterns. Conventional is glyphosate used pre-seeding every year, GT is a glyphosate-tolerant crop grown at a frequency of once in 4 or 3 years with a pre-seeding application of glyphosate.

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<thead>
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<th>Use pattern</th>
<th>Initial frequency of resistance</th>
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<tr>
<td></td>
<td>$10^{-8}$</td>
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<tr>
<td>Conventional</td>
<td>17</td>
</tr>
<tr>
<td>GT every 4th year</td>
<td>10</td>
</tr>
<tr>
<td>+ no glyphosate pre-seeding in GT</td>
<td>13</td>
</tr>
<tr>
<td>+ no glyphosate for 1 year after GT</td>
<td>12</td>
</tr>
<tr>
<td>+ no glyphosate for 2 years after GT</td>
<td>16</td>
</tr>
<tr>
<td>GT every 3rd year</td>
<td>9</td>
</tr>
<tr>
<td>+ no glyphosate pre-seeding in GT</td>
<td>11</td>
</tr>
<tr>
<td>+ no glyphosate for 1 year after GT</td>
<td>12</td>
</tr>
<tr>
<td>+ no glyphosate for 2 years after GT</td>
<td>13</td>
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</table>

Control of weed seed set has little impact on the development of resistance in these simulations. More than 80% weed seed set reduction is needed in the year the glyphosate-tolerant crop is grown to delay resistance by 1 year. In contrast, the level of pre-seeding control obtained by glyphosate has a significant impact on the development of resistance. A delay in resistance of up to 4 years occurs when 69% of L. rigidum emerges and is controlled pre-seeding, compared to 90%. With a greater proportion of the weeds emerging in crop, the use of a glyphosate-tolerant crop once in 4 years becomes a more attractive option to delay resistance.

These simulations assume that the first use of glyphosate is in the year the glyphosate-tolerant crop is grown. However, there will be numerous situations where an extensive history of pre-seeding glyphosate use exists. Simulations suggest that the longer the history of pre-seeding glyphosate applications, the more rapid the development of resistance once the glyphosate-tolerant crop is grown.

CONCLUSIONS

In southern Australia, one species, L. rigidum, contributes the vast bulk of populations with herbicide resistance. The reasons for this are the ubiquitous nature of this weed across southern Australia, its high densities in cropping areas, and the widespread use of herbicides, particularly the more resistance prone modes of action, for the control of this species. Clearly herbicide resistance will continue to develop in numbers of species and numbers of populations so long as herbicides remain the tool of choice for weed control.

On current predictions, the introduction of herbicide-tolerant crop varieties will result in only one additional herbicide mode of action, glufosinate, for southern Australian cropping systems. All other herbicide-tolerant crops will only provide new uses for existing modes of action. Judicious use of these herbicide-tolerant crop varieties and their associated herbicides is necessary to reduce the selection for resistant weed types. The challenge will be to introduce herbicide-tolerant crop varieties in a way that achieves long term benefits by minimising weed resistance.

REFERENCES


