Herbicide resistance: an imperative for smarter crop weed management

Michael Walsh and Stephen Powles

Western Australian Herbicide Resistance Initiative, School of Plant Biology, University of Western Australia, Crawley WA 6009. www.wahri.agric.uwa.edu.au

Abstract
In most world cropping systems the evolution of herbicide resistant weeds is becoming a major issue. This problem has become most severe in Australia. In the broad-area rain-fed cropping systems of southern Australian, herbicide resistance is a widespread problem threatening cropping profitability and sustainability. Widespread herbicide resistance has forced changes in agronomic and herbicide practices towards more diversity. Judicious herbicide mixtures and rotation can reduce the selection pressure for resistance to any one specific herbicide. Additionally, agronomic practices such as the adoption of delayed seeding and increased seeding rates can also reduce selection pressure by reducing in-crop weed populations. However, these techniques are not without problems or limitations. At grain harvest, the use of machinery to capture, collect and render weed seed non-viable is a very effective technique for reducing annual weed populations. The adoption by Australian farmers of the current limited technology is clear evidence of the value placed on the use of these alternative crop weed control practices. The continued march of herbicide resistance evolution more than justifies continuing research and development efforts to develop integrated strategies and smarter herbicide use so as to achieve sustainable crop weed management.

Media Summary
The evolution of herbicide resistance in prominent crop weeds threatens sustainable cropping, worldwide. This problem is now widespread in Australian cropping. Greater diversity in herbicide and agronomic practices for the effective management of weeds within cropping systems is needed in cropping systems, worldwide.

Keywords
Herbicide resistance, diversity, weed seed collection, chaff cart, annual ryegrass, wild radish

Introduction
In most broad-area grain cropping systems, herbicides dominate for crop weed control. For example, in Australia, large cropping areas, expensive labour, short growing seasons, fragile soils and the imperative to minimize production costs (slim profit margins) all result in herbicides being a vital component of cropping systems. Herbicides enable timely, early season crop seeding as well as no-till, stubble retention farming systems, which now dominate crop production enterprises across vast areas of southern Australia. There can be no doubt that herbicides have made major contributions to crop productivity and to the sustainability of agricultural systems in many parts of the world. Indeed, in the current broad-area cropping systems there are limited alternative practicable technologies for crop weed control.

Because of the many advantages of herbicides there is almost universal reliance on herbicides for crop weed control in industrialized nations. Currently, there is also rapid adoption of herbicide technology in cropping systems in developing nations. Despite the many advantages of herbicides there can be biological repercussions of over-reliance on herbicide technology. Herbicide treatment of massive populations of genetically variable weedy plant species represents a potent evolutionary selection pressure for individuals with genetic traits enabling them to resist the herbicide treatment. Consequently, herbicide resistant weed populations have evolved in many parts of the world, following persistent herbicide selection. Currently, the largest herbicide resistance problem in world cropping exists in Australia, in the widespread, genetically variable, diploid crop weed, annual ryegrass (*Lolium rigidum*). In the agricultural development of much of temperate southern Australia, in the period 1820-1960, ryegrass was planted and nurtured as a pasture. During this period of integrated crop and livestock production ryegrass was a vital component of pasture phases. However, in the 1970s, improvements in the profitability of crop production (principally wheat) coincided with declining returns from livestock enterprises. Consequently, there was a general shift of the farming systems into intensive cropping rotations with a considerable de-emphasis of on pasture and livestock production. This change to intensive cropping was in part enabled by the availability of highly effective herbicides that enabled in-crop selective weed control. These herbicides enabled a reduction in soil cultivation and stubble burning, practices which were found to be highly destructive to the fragile cropping soils of southern Australia. An integral component of these cropping systems was the use of herbicides for the control of the abundant ryegrass populations present on vast areas of southern Australia (Powles and Matthews, 1992). The combination of huge numbers of genetically diverse, cross-pollinated ryegrass populations with cropping systems devoted to minimal tillage, minimal diversity and strong herbicide reliance has resulted in the widespread evolution of herbicide resistant ryegrass populations (Powles and Matthews, 1992). Resistance has become widespread and extends simultaneously across many herbicide chemistries (multiple herbicide resistance). For example, herbicide resistance was unknown in the early 1970s across the 8 million hectare grainbelt of Western Australia but by 2001 there was widespread resistance to crop selective herbicides in annual ryegrass (*Lolium rigidum*) ((Llewellyn and Powles, 2001; Walsh et al., 2001)) and wild radish (*Raphanus raphanistrum*) ((Llewellyn and Powles, 2001; Walsh et al., 2001)). A recent similar survey in South Australia also revealed high levels of herbicide resistance in ryegrass (C. Preston, personal communication). Increasingly, multiple resistance across many herbicides is dramatically reducing the herbicide options available for the control of ryegrass and wild radish in cropping systems.

The widespread evolution of herbicide resistant weed populations within intensive crop production systems would not be a major threat to the sustainability and profitability of cropping systems if new herbicide modes of action were being introduced to replace those herbicides failing due to resistance. However, the rate of introduction of new herbicides for world agriculture has slowed dramatically. This is due to the difficulty in discovering new herbicide modes of action with the necessary environmental properties and the substantial reduction in herbicide discovery programs because of the rationalisation of international agrichemical corporations. A decade ago there were more than 10 multi-national corporations with major herbicide discovery programs, whereas in 2004 there are only four. New herbicide discovery will occur but introduction of new herbicide modes of action is now, and will continue to be, rare. As there will not be the regular introduction of new herbicide modes of action able to control herbicide resistant weeds, there is a strong imperative to use the currently available herbicide resources in more sustainable ways. Other agronomic means to help manage crop weed populations, so as to reduce herbicide reliance, also need to be developed.

For the reasons outlined above, herbicide resistance has been a major problem for Australian cropping at least for the past decade. Resistance is only now becoming a major problem in many other parts of the world. Some of the practices that have been identified to help manage the herbicide resistance challenge in Australian farming systems may be useful in other parts of the world and are outlined below. Germane to these developments are the recognition that weed management must be built on a solid foundation of good crop agronomy. A factor critical to long-term weed management is the principle of avoiding heavy reliance on single control methods such as one highly effective herbicide. An integrated approach is required that incorporates as wide a range of weed control methods as possible. A critical objective is minimising the return of weeds seeds to crop fields.

Altered agronomic and herbicide practices before and at crop seeding.

The adoption of zero tillage is recent but now widespread in Australian cropping. One of the advantages of zero tillage has been the ability to seed the crop earlier in the growing season, with reliance on post-emergent herbicides to control weeds. The widespread evolution of ryegrass with resistance across the majority of in-crop selective herbicides has forced changes to this system. In response, a delay in the date of crop seeding and innovative use of non-selective herbicides (glyphosate and paraquat) is occurring in some areas of southern Australian croplands. In areas with a sufficiently long growing season, delaying crop seeding by two to three weeks enables a much greater percentage of the annual weed emergence flush to occur following the season-breaking autumn rains. This allows pre-seeding weed control using non-selective herbicides glyphosate or paraquat, to which resistance is currently rare. However, although effective in controlling the initial emergence of weeds following the break of the season there can be yield penalties associated with delayed crop seeding ((Anderson and Sawkins, 1997)). Additionally, the increased reliance on the non-selective herbicide glyphosate is now causing concern, with cases of resistance now evident ((Powles Stephen et al.)1998; (Pratley et al., 1999), Wakelin et al, 2003, Neve et al 2004). There is a real concern that there will be the widespread development of glyphosate resistance

(Neve et al 2003a). Population genetics modelling has produced recommendations of a judicious sequence of glyphosate followed by paraquat (double knockdown) to decrease the likelihood of glyphosate resistance evolution (Neve et al 2003b).

An increase in seeding rates has been widely adopted by Australian crop producers as a means of reducing early season crop competition from dominant weed species as well as increasing the yield potential of cereal crops. Increased crop seeding rates have been demonstrated to reduce the impact of weed populations across many regions of the southern Australian wheatbelt ((Peltzer, 1999); (Minkey, 2002)). Consequently, elevated seeding rates, especially for wheat crops, is now a standard practice. Wheat seeding rates have probably increased 25% nationally over the decade 1994-2004, driven by herbicide resistance and other agronomic advantages. However, despite a positive impact of higher crop seeding rates in suppressing weed growth, and pre-seeding weed control with non-selective herbicides, these practices alone or combined cannot adequately control weed populations. Therefore, there remains the need to develop additional weed management procedures, in addition to judicious herbicide usage.

Use of bio-economic and population genetics modeling for smarter herbicide usage and crop weed management

Too often, decisions about weed control in crops are made on a single season basis with insufficient consideration of the long-term dynamics. Control practices for crop weeds (or decisions not to control small infestations) have long-term effects on the soil seedbank and therefore the population dynamics of weed species, as well as influencing short and longer-term profitability of cropping enterprises. Better decision making, taking into account longer-term weed population dynamics, and a means of tracking outcomes are required. To assist grain growers and advisers, bio-economic models have been developed that track the population dynamics of ryegrass (Pannell et al 2004) and wild radish (Monjardino et al 2003) and their influence on the profitability of various crop and pasture options within Australian cropping systems. These bio-economic models enable the simulation of the biological and economic impact of a range of herbicide and agronomic strategies on crop weed numbers and on profitability of cropping over many years of simulation. The impact of many different strategies can be simulated and the results can support decisions that take into account long-term impacts. Equally, population genetic models simulating the development of herbicide resistance (Neve et al 2003a,b) can be very useful in designing sustainable herbicide use strategies.

Collection and destruction/removal of weed seeds during the harvest operation

The targetting of weed seeds during the harvest operation has been proven as an effective means of reducing weed seed return to crop fields. Several studies have identified the potential for collecting and removing the seed of annual crop weed species during the harvest operation ((Fogelfors, 1982; Gill and Holmes, 1997; Matthews et al., 1996; Shirtliffe et al., 2000); (Walsh, 1996)). When infesting crops, the two most problematic weed species of Australian cropping, annual ryegrass and wild radish, reach maturity at a similar time to the crop. For both species the majority of their seeds remain attached to the plant at or above the height of the seed heads of crops such as wheat, lupins and canola. Consequently, many of these weed seeds can be collected by and pass through the harvester during the harvest operation. Usually these processed weed seeds are immediately returned to the field in either the chaff or straw residues, where they add to the soil seedbank. However, there is an opportunity to collect and remove weed seeds as they pass through the harvester, thereby preventing them from returning to the field and entering the seedbank. Two commercially adopted methods that target weed seed are an extension to harvester sieves that enable weed seed to be captured (Matthews et al 1996), or the collection of the weed seed containing chaff fraction by trailing chaff carts. These carts are towed behind grain harvesters with the aim of collecting all chaff material as it exits the harvester. This fraction of the harvest residue contains the greatest proportion of weed seed. For example it has been estimated that up to 95% of ryegrass seed that enters the harvester exits in the chaff fraction ((Walsh and Parker, 2002)).

Annual ryegrass seed collection by chaff carts

Harvesters with attached chaff carts were evaluated in wheat crops in 1999 to determine the efficacy of chaff carts in the collection and removal of ryegrass seed. The efficiency of ryegrass seed collection was determined on four commercially operating harvesters in wheat crops with areas of naturally occurring ryegrass infestations. It was determined that 70-80% of annual ryegrass seed entering these harvesters was collected and removed into the chaff cart during the harvest operation ((Walsh and Parker, 2002)).

Wild radish seed collection by chaff carts
The proportion of wild radish seed that can be removed during the harvest operation is much higher than that for annual ryegrass. In studies conducted during the 2001 harvest there was almost complete collection and removal of wild radish seed that entered the harvester during the harvest of a wheat crop ((Walsh and Parker, 2002)). Seed were primarily collected in the grain sample (75%) but there was also a significant proportion collected in the chaff fraction (20%). Overall, when a chaff cart was attached, 95% of the wild radish seed that entered the harvester was collected and removed during harvest.

Baling of chaff material
Where chaff material is collected during the grain harvest operation using chaff carts the collected material is normally left in heaps in the field and is subsequently burnt to destroy the weed seed. An alternative to the in-situ burning or grazing of chaff heaps is to bale all the chaff and straw material produced by the harvest operation. Baling allows for the collected straw and chaff material, as well as the weed seeds they contain, to be easily transported from fields. Currently the opportunity exists for this material to be used as a livestock feed source. There are two methods being used to bale the chaff and straw residues. The first uses the "Chafftop" which is a device attached to the rear of the harvester that collects the chaff material exiting the harvester and deposits it on top of the straw windrow. The placement of the chaff material on the top of the windrow is the reverse to the conventional system and increases the potential for chaff material to be collected during a subsequent baling operation. These windrows are then baled at some stage after the completion of harvest using a conventional baling system. The second option is to direct all chaff and straw material into a trailing baler that is attached to and driven by the harvester. This system potentially increases the amount of baled material and can improve the efficiency of weed seed collection by avoiding the deposition and subsequent collection of a windrow. Both systems allow for the removal of weed seeds in baled material that also has an economic value.

Destruction of weed seed during grain harvest
The logistics of trying to handle the vast quantities of chaff material produced during the harvest operation has instigated the concept of treating this chaff material to control the weeds seeds contained within it as part of the harvest operation. In excess of 100 m^3/ha of chaff material is produced during the harvest of a typical wheat crop grown in southern Australia. There are enormous difficulties in collecting and handling this material and there is little doubt that this has restricted adoption of the chaff cart technology. An alternative is the processing of the chaff material sufficient to destroy weed seeds as they exit the harvester. If weed seeds could be rendered non-viable by physical or chemical treatment as they exit the harvester this would remove the need to collect and handle large volumes of chaff material. Although there is limited research in this area a study conducted in Oklahoma, USA indicated that hammer mills and roller mills could be used to control cheat (*Bromus secalinus*) seed during harvest ((Gossen et al., 1998)). Harvestaire®, a Western Australian agricultural engineering company, has been pursuing this idea in the current development of their "Rotomill". This device can be mounted beneath an extension of the top sieve at the rear of the harvester. Chaff material would be processed by the "Rotomill", sufficient to destroy any weed seeds, as they exit the harvester. Another innovative idea is the development of a system for treating chaff material with harvester engine exhaust gases. This research is being pursued by Dr. John Matthews, University of Adelaide, where exhaust gases from the harvester motor are being used to sterilise weed seeds in the chaff fraction.

Summer weed seed control
Widespread adoption of zero tillage with crop stubble retention and the reduction in livestock grazing of stubbles has combined to create a situation where weed seeds now remain on or close to the soil surface. In the Mediterranean type Australian agro-ecosystem, weed seeds are shed to the soil surface in early summer and remain relatively undisturbed on the soil surface during the hot, dry summer-autumn months (December to April). The combination of huge fields (400+ ha), flat terrain and weed seed on the surface over summer presents an opportunity to implement physical or herbicide weed seed control practices, notwithstanding the logistical problems such as large energy requirements, specialised engineering and costs. Thus there appears to be an opportunity for a much needed, new weed control practice to be developed for this particular situation, but at this stage, there is no "close-to-market" technology available in this potential area of weed control. However, studies have identified the potential for late-summer early-autumn herbicide applications prior to the commencement of the growing season (Walsh et al.

2004). Certain residual herbicides, applied during this period before the season opening rains, retain activity and can control ryegrass germination/early seedling growth up to two months after the rainfall event. A significant advantage of this option is that crop seeding can commence immediately following the opening rains, thereby avoiding crop seeding delay in the knowledge that ryegrass has been controlled.

Diversity in crops and pastures.
Profitable and sustainable agro-ecosystems maximise the growth and yield of valuable plants while minimising reproduction of weedy species. Diversity in agro-ecosystems can contribute to more robust and sustainable systems. Currently, in areas of Australia where herbicide resistance is a major problem a contributing factor is limited diversity in wheat-dominated agro-ecosystems. There is much less resistance in areas where a more diverse system embraces livestock and phases of pasture interspersed with phases of cropping. A more diverse system enables diversity in herbicide and other weed control tools. In many cropping systems worldwide there is increasing intensity and decreasing diversity in the range of crops under cultivation. For example, US and Argentinean soybean production is now dominated by glyphosate-resistant soybeans, resulting in an over-emphasis on glyphosate for weed control. In some of these regions glyphosate-resistant soybean is grown in rotation with glyphosate-resistant cotton and/or maize, often under minimum tillage systems. In such situations there is insufficient diversity of weed control with over-reliance on glyphosate and as a result glyphosate resistant weeds will inevitably evolve in these regions (Powles 2003). Diversity in crop choice and in weed control strategies have the best chance of long-term sustainability and therefore, within economic realities, diversity should be strived for. For example, pastures and livestock can offer considerable diversity in many parts of southern Australia in which wheat is the major crop. Phases of pasture provide the opportunity to utilise the grazing animal for weed control, to use different herbicides to those used in cropping phases and to minimise weed seed production. In North and South America, glyphosate resistant crops should be grown in rotation with non-glyphosate resistant crops. An example would be rotation between glyphosate-resistant soybean with conventional maize, or vice versa. Equally, growers in these regions should increase diversity by utilising both glufosinate and glyphosate-resistant crops.

A currently worrisome trend in some important intensive rice-cropping regions within Asia is a decrease in diversity due to direct seeding (reduced tillage) and reliance on one class of herbicides (acetolactate synthase inhibiting herbicides). Herbicide resistance will inevitably evolve in such systems and more diverse practices are required if the benefits of reduced tillage and herbicides are to be retained in the medium to long term.

Conclusions
It is clear that herbicides remain the most efficient technology for large-scale weed control, worldwide. However, the continued increase in evolved herbicide resistance in prominent weed species must lead to change in the way herbicides are used. As there is a paucity of new herbicide modes of action being commercialised there is an imperative to maximize the longevity of the available herbicide resource. To do this requires more pro-active herbicide usage than has been the case until now. Herbicide resistance management strategies need to be implemented that aim to maximise herbicide longevity in farming systems. Maximising the diversity of crops and weed control tools employed is essential for sustainable crop weed management. In the future, bio-economic and population genetics simulation models will assist more sustainable herbicide usage. Careful crop and herbicide rotation together with herbicide sequences and mixtures will be required. Equally, non-herbicide agronomic and biological techniques will be employed to reduce herbicide reliance thereby helping to ensure greater longevity of the precious herbicide resource.

Acknowledgment
WAHRI is funded by the Grains Research and Development Corporation.

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