Review

Received: 28 October 2013 Revised: 8 January 2014 Accepted article published: 20 January 2014 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/ps.3727

Current state of herbicides in herbicide-resistant crops

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Abstract

Current herbicide and herbicide trait practices are changing in response to the rapid spread of glyphosate-resistant weeds. Growers urgently needed glyphosate when glyphosate-resistant crops became available because weeds were becoming widely resistant to most commonly used selective herbicides, making weed management too complex and time consuming for large farm operations. Glyphosate made weed management easy and efficient by controlling all emerged weeds at a wide range of application timings. However, the intensive use of glyphosate over wide areas and concomitant decline in the use of other herbicides led eventually to the widespread evolution of weeds resistant to glyphosate. Today, weeds that are resistant to glyphosate and other herbicide types are threatening current crop production practices. Unfortunately, all commercial herbicide modes of action are over 20 years old and have resistant weed problems. The severity of the problem has prompted the renewal of efforts to discover new weed management technologies. One technology will be a new generation of crops with resistance to glyphosate, glufosinate and other existing herbicide modes of action. Other technologies will include new chemical, biological, cultural and mechanical methods for weed management. From the onset of commercialization, growers must now preserve the utility of new technologies by integrating their use with other weed management technologies in diverse and sustainable systems.

Keywords: bioherbicide; biotechnology; crop; weed; herbicide; glyphosate; resistance; tolerance; RNAi; weed management

1 INTRODUCTION

Weed management practices have evolved over the past century from cultural and mechanical practices to mechanical and chemical and then to chemical-only practices. Today, synthetic chemical herbicides are used globally to control weeds in all major field crops. In much of North and South America at the turn of the century, chemical weed management had evolved to using only glyphosate in glyphosate-resistant (GR) crops. Initially, many experts were sceptical about the value of GR crops, but Monsanto was a strong champion of the technology, and today nobody can debate that the use of glyphosate in GR crops dramatically changed weed management practices and increased crop yields and profitability for many growers.[1] Nevertheless, weeds are still the most important pest problem and the greatest limitation on crop yield,[2,3] and growers need new weed management practices to meet the food, fibre and fuel demands for a world population projected to grow to 9.3 billion in 2050.[4]

Two important events occurred in 1996 that have greatly influenced weed management – the first GR crop was introduced[5] and the first GR weed was reported.[6] GR weeds did not evolve initially in areas where GR crops were being introduced and thus did not slow the adoption of the technology. Growers rapidly adopted GR crops wherever they became available, and in doing so usually relied exclusively on glyphosate for weed management.[7,8] Some thought using glyphosate alone in GR crops would be sustainable, but the extreme overuse of glyphosate over wide areas eventually led to the widespread evolution of GR weeds. Currently, 24 weed species are known to be resistant to glyphosate; 11 of these species have biotypes that are resistant to glyphosate and other herbicide types.[6]

As GR weeds spread, growers lose many of the advantages they enjoyed using glyphosate in GR crops and must now adjust their weed management practices, often relying on herbicide practices that were available before the introduction of GR crops.[9] Fortunately, most of the herbicides that were available before GR crops are still registered and reasonably effective in controlling GR weeds.

2 HERBICIDE USE AND DISCOVERY

The discovery of synthetic herbicides in 1945 was a major technical achievement that quickly changed weed management practices. Synthetic herbicide technology rapidly improved with respect to efficacy, weed spectrum, lower use rates and safety to the crop, user and the environment. Today, growers have access to more than 200 herbicide active ingredients with 29 different modes of action, including some herbicides for which the mode of action is unknown,[10,11] but mainly use herbicides from the six modes of action that have close to 80% of the herbicide market.[12]

Today, growers rely heavily on herbicides for weed management and have made herbicides the largest chemical sector of the $US 85 billion crop protection market. Herbicide sales are currently

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at about $US 17 billion annually, significantly more than sales of fungicides or insecticides.[13] Herbicide use is growing in both developing and developed countries.[14] The value of the global herbicide market grew by 39% between 2002 and 2011 and is projected to grow another 11% by 2016.[12,14] Post-patent herbicides are the largest and most rapidly growing market segment, particularly the value-added generic segment where formulations have been improved.

Herbicides remain the most effective, efficient and economical way to control weeds, and even with the plethora of post-patent and lower cost generic products, the herbicide market continues to grow in value. The key driver for this growth is the need to achieve higher yields for an ever-increasing global population and the corresponding demand for grain, both for human and animal consumption. Ironically, the rapid spread of HR weeds is also increasing the use of herbicides because the first reaction of many growers when they discover HR weeds in their fields is to use higher rates and alternative herbicides before changing cultural practices.

The 1970s and 1980s were the golden age for herbicide discovery.[13] Growers saw a steady flow of non-selective and selective herbicides with new modes of action. Key herbicides included glyphosate and glufosinate, as well as a large number of selective herbicides that inhibited acetolactate synthase (ALS), acetyl coenzyme A carboxylase (ACCase), hydroxyphenylpyruvate dioxygenase (HPPD), phytoene desaturase (PDS) and protoporphyrinogen oxidase (PPO). Everything seemed possible through chemistry. The success of the 1970s and 1980s and the ability to use glyphosate in GR crops reduced the incentive to discover herbicides, but no one thought the last new herbicide mode of action would be discovered in 1982.[15]

By almost any measure, herbicide innovation has greatly slowed.[13,15] New herbicide products today tend to be premixed formulations of existing actives with known modes of action, new salts and esters or new actives with minor chemical modifications that claim to improve weed efficacy and spectrum, crop safety, reduced rates and/or soil residual activity. Recent examples of such advancements include the synthetic auxins aminocylcopyrachlor and halauxifen-methyl, the ACCase inhibitor pinoxaden, the PPO inhibitor saflufenacil, the HPPD inhibitors bicyclopyrone, tembotrione and pyrasulfotole, the ALS inhibitor trifamone, the cellulose biosynthesis inhibitor (CBI) indaziflam and very-long-chain fatty acid (VLCFA) inhibitors pyroxasulfone and fenoxasulfone. Sometimes, new chemical analogues can control weeds that are resistant to other chemicals within a mode of action, but analogues are not a general solution for HR weeds because weeds are often cross-resistant.

The spread of HR weeds has created more incentive for industry to discover new herbicide modes of action, but the standards that must be met for weed efficacy and environmental and toxicological safety are higher than in the past.[15] The major herbicide markets are crowded with aging active ingredients that are under constant threat from lower cost generics. Glyphosate is still very effective for many growers, and, until the advent of widely distributed GR weeds, herbicide companies perceived less market opportunity and reacted by reducing their investment in herbicide discovery. The number of chemical companies trying to discover herbicides declined from about 45 in 1970 to six companies today – Syngenta, Bayer, BASF, Dow, DuPont and Sumitomo.[9,16] Fortunately, several of the remaining companies have large and growing herbicide discovery programs.

The time and cost to commercialize new herbicides continue to increase and are a major barrier. Today, the commercialization of a new herbicide takes a decade at a cost of over $US 250 million.[12] Current estimates are that scientists must screen more than 200 000 chemicals to discover one new commercial herbicide, one that does not have a new mode of action. Evaluating such large numbers is easier than in the past because scientists have access to large chemical libraries, combinatorial chemistry and automated high-throughput testing systems. Scientists also have more tools, including access to various 'omics' technologies such as functional genomics, transcriptomics, proteomics, metabolomics and physionomics.[9,13] Surprisingly, it has not been difficult to find inhibitors of plant enzymes with unique modes of action. The difficulty has been to find chemical inhibitors of lethal target sites with the physicochemical properties to be effective when applied to the whole plant.[17]

Traditionally, the most difficult aspect in herbicide discovery has been finding selective chemical modifications that make herbicides safe to key crops while still maintaining activity on key weeds. Transgenic HR crop technology can eliminate that difficulty by allowing the opportunity to alter crop sensitivity to broader-spectrum, more robust herbicides, thus increasing their overall utility.[18] The discovery of herbicides with broad-spectrum weed control is now more valuable than the discovery of herbicides with inherent crop selectivity. However, the associated HR crops with the new herbicide will shift some of the weed management value away from the herbicide to the seed, or more accurately to the seed company.

3 IMPACT OF GLYPHOSATE-RESISTANT CROPS ON HERBICIDE USE

For 60 years before the introduction of GR crops, growers used selective herbicides for weed management. Growers had to spend time identifying weeds and designing strategies with selective herbicides to control them. After GR crops, a single application of glyphosate at almost any timing controlled all weeds, even weeds that were resistant to other herbicides.[5,19] GR crops made weed management easy, effective and efficient while reducing the environmental impact of weed management practices, primarily by facilitating change to less tillage. Growers recognized the advantages of being able to use glyphosate and rapidly adopted it in GR soybeans [*Glycine max* (L.) Merr.], corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), canola (*Brassica napa* L.), alfalfa (*Medicago sativa* L.) and sugarbeets (*Beta vulgaris* L.).[20] Currently in the United States, 93% of soybeans are GR and almost all of the 85% of the corn that is HR is GR.[21]

In practice, glyphosate and glufosinate were new modes of action for growers in the 1990s when HR crops were introduced that allowed their use in-crop for the first time. Glyphosate in GR crops was initially very effective and easier to use than the selective herbicides it replaced, and it even reduced the amount of herbicide that growers needed to apply.[22,23] However, the value of GR crops began to decline with weed spectrum shifts to glyphosate-tolerant and glyphosate-resistant weeds. Today, most growers still use glyphosate but also rely more on selective herbicides and tillage as they did before the introduction of GR crops. Overall herbicide use in GR crops has increased significantly since the onset of GR weeds.[24]

Fortunately, many of the herbicides that were available before growers changed to glyphosate and GR crops are still available (Table 1). For example, photosystem II (PSII) inhibitors such as

Table 1. Herbicide types commonly used in corn, soybeans and cotton, selective (S) and herbicide-resistant crop enabled (R)

Herbicide type (group)[a]	Corn	Soybeans	Cotton	Canola
ALS-inhibitors (B)	S	S + R	S	S + R
ACCase-inhibitors (A)	S + R	S	SS	S
HPPD and PDS inhibitors (F)[b]	S	R	R	
Synthetic auxins (O)[b]	S + R	S + R	R	
PPO inhibitors (E)	S	S	S	
PSII inhibitors (C)	S	S	S	
Cell division inhibitors (K)	S	S	S	S
Lipid biosynthesis inhibitors (N)	S	S	S	S
Auxin transport inhibitors (P)	S			
Glyphosate (G)[c]	R	R	R	R
Glufosinate (H)[c]	R	R	R	R

[a] Herbicides grouped according to the Herbicide Resistance Action Committee, http://www.plantprotection.org/hrac.
[b] Auxin and HPPD resistance crops are not commercial but still under development.
[c] Glyphosate, glufosinate and paraquat (D) are also used before crop emergence for burndown.

triazine and urea herbicides, lipid synthesis inhibitors such as *S*-metolachlor and phytoene desaturase (PDS) inhibitors such as clomazone are still useful selective herbicides that provide soil residual activity on key weeds. Other selective herbicides such as inhibitors of ALS, PPO and ACCase are still widely used and have high efficacy on many weeds. Commercially, there are 50 ALS-inhibiting herbicides from five different chemical classes, 29 PPO-inhibiting herbicides from nine chemical classes and 19 ACCase-inhibiting herbicides from three chemical classes. The most recent PPO and ACCase introductions, saflufenacil and pinoxaden, have been successful products.

Other herbicides will also have utility. For example, paraquat is a widely used, non-selective photosystem I (PSI)-inhibiting herbicide applied as a burndown herbicide before the crop has emerged or as a directed spray with specialized application equipment. Its lack of soil residual allows rotational crop flexibility, similarly to glyphosate and glufosinate. The weed spectrum of paraquat is also similar to that of glyphosate and glufosinate, but its fast action does not allow it to translocate well enough to control perennial weeds, and its mammalian toxicity imposes significant use and handling restrictions. New formulations of paraquat have the potential to overcome these toxicity concerns and make paraquat more broadly useful.[25,26]

4 IMPACT OF GLYPHOSATE AND MULTIPLE-HERBICIDE-RESISTANT WEEDS ON HERBICIDE USE

4.1 Overuse

The ability to use glyphosate in GR crops could have increased the diversity of weed management practices (Table 1). Glyphosate was a new mode of action, and GR crops do not require growers to apply glyphosate. However, glyphosate was good enough for many growers only to use glyphosate year after year, and the use of selective herbicides decreased as the use of glyphosate in GR crops increased.[20,27,28] For example, the number of herbicide actives used on at least 10% of the US soybean area declined from 11 in 1995 before GR crops were available to just one herbicide active in 2002 – glyphosate.[29] Today, glyphosate still dominates the global herbicide market with 65% of the total herbicide volume, while atrazine is a far distant second with less than 6%.[30] The amount of glyphosate that growers use continues to increase; glyphosate use increased from 30 million to 45.5 million kg during the time period from 2005 to 2012.

The heavy reliance on glyphosate alone across vast areas of GR crops put unprecedented selection pressure on weeds to evolve resistance.[5,31] Weeds did not evolve resistance to glyphosate as rapidly as to most other herbicides, but the extreme selection pressure eventually led to the widespread evolution of GR weeds. As some growers describe, the technology was 'too easy, too cheap for too long'. Currently, almost all, (98%) of US soybeans are treated with herbicides.[29] By far the most commonly used herbicide is still glyphosate, currently applied to 96% of these soybeans.

The overuse of glyphosate opened a Pandora's box of GR weeds. The widespread distribution of GR weeds has reached tipping point and is now forcing growers to change their weed management practices. So far, the first response of most growers to GR weeds in GR crop systems has been chemical – to use higher rates of glyphosate and mixtures of glyphosate with other herbicides more often. Proponents characterize this change as a reversion to the more diverse weed management practices used in the past, but critics characterize it as an increasing reliance on older and less preferred herbicides. Without doubt, GR weeds are forcing growers to rely increasingly on selective herbicides with narrow safety margins. The older selective herbicides often cause some short-term crop phytotoxicity, but that phytotoxicity usually does not reduce yield. The yield loss from not controlling weeds, particularly GR weeds, is always greater than any possible yield loss from selective herbicide treatments.[32]

Unfortunately, the weeds that evolve herbicide resistance tend to evolve resistance to multiple herbicide types. Currently, 65 species have evolved resistance to multiple herbicide types,[6] and these multiple HR weeds are a serious threat to the sustainability of current crop production practices.[31,33–35] Some cotton growers are nearly out of options and must use all available weed management tools at great expense to control multiple HR Palmer amaranth (*Amaranthus palmeri* S. Wats.) – up to seven herbicide modes of action and hand weeding.[24] The diversity of herbicides being used is increasing in other crops also. In 2005, 2,4-D, trifluralin and chlorimuron were the most popular herbicides in soybeans, with 6, 4 and 4% of the market respectively. Currently, the top three most popular herbicides are 2,4-D, flumioxazin and chlorimuron, each having 11% of the market.

The increased use of glyphosate with selective herbicides, particularly broad-spectrum herbicides with soil residual activity, is a strong indication that growers are making a positive change in their resistant weed management practices, but many growers waited too long. Nearly 50% of US growers already have GR weeds in their fields.[36] There are not currently enough effective herbicide options in some situations to manage HR weeds. Growers in these areas desperately need new weed management technologies for sustainable long-term solutions. The discovery of herbicides with new modes of action would be a great help, but no herbicide, no matter how effective, will be the total solution – weeds will eventually evolve resistance to any herbicide.

4.2 New herbicide-resistant crops

The genetically modified HR crop revolution has been based on remarkably few genes so far. In fact, most of the impact

Table 2. Update summary of publicly announced transgenic multiple-herbicide-resistant crops[34,37]

Herbicide types	Crops
Glyphosate and glufosinate	Soybeans, corn and cotton
Glyphosate and ALS inhibitors	Soybeans, corn and canola
Glyphosate, glufosinate and 2,4-D	Soybeans and cotton
Glyphosate, glufosinate and dicamba	Soybeans, corn and cotton
Glyphosate, glufosinate and HPPD inhibitors	Soybeans and cotton
Glyphosate, glufosinate, 2,4-D and ACCase inhibitors	Corn
Glufosinate and dicamba	Wheat

has been due to just one gene, *cp4 epsps*, which encodes for glyphosate-resistant 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS, EC 2.5.1.19). However, the value of *cp4 epsps* alone and of crops being resistant to just glyphosate is ending as GR weeds spread.[37,38] Most companies involved in herbicide discovery are also involved in the discovery of new herbicide traits.

The days of the major HR row crops being resistant to glyphosate alone are over; new HR crops need to be resistant to more than just glyphosate. Currently, Monsanto, Dow, Bayer, Syngenta and BASF are developing new crop herbicide resistance traits in combination with glyphosate resistance.[39] Because of the lack of new broad-spectrum herbicides, the most common current strategy is to develop multiple HR crops with resistance to glyphosate, glufosinate and one of five other herbicide types (Table 2). Crops resistant to glyphosate and glufosinate are already widely available. After governmental approval, the other resistant crop technologies should be widely available to growers, as many seed companies have recently made agreements to get access to these new herbicide traits. These multiple HR crops will enable a very potent array of new options with existing herbicides, but will not be the total weed management solution because HR weeds already exist to all these herbicide types (Table 3).[27,34]

The first two new HR crop technologies likely to have a significant impact will be broadleaf crops resistant to synthetic auxin herbicides: one technology for 2,4-D that was discovered in the 1940s and the other for dicamba that was developed in the 1960s.[40,41] Broadleaf crops are generally sensitive to auxin herbicides, and so auxin-resistant soybeans and cotton would enable new uses of auxin herbicides that still have broad utility. In spite of widespread use for 60 years, relatively few weed species have evolved resistance because of the complexity of the site and mode of action of auxin herbicides.[6] New formulations with less volatile salts and drift control adjuvants will help reduce off-target movement and could reinvent auxin herbicide technology.[42]

Crops with resistance to HPPD-inhibiting herbicides will likely be commercialized soon after auxin-resistant crops and could have a significant impact on weed management practices because HPPD-inhibiting herbicides control key weed species with some soil residual activity. However, the spread of HPPD-resistant weeds, particularly HPPD-resistant waterhemp, could limit the adoption of this technology.[8] As with synthetic auxin herbicides, corn generally has some native tolerance to HPPD herbicides, but soybeans and cotton are sensitive. Two traits are under development in soybeans and cotton that would enable new uses for HPPD herbicides.[43,44]

Crops resistant to ACCase- and ALS-inhibiting herbicides have been sold commercially and can be readily created by both transgenic and non-transgenic methods. These modes of action continue to have utility, but their use is often restricted to mixtures because of the widespread distribution of ALS- and ACCase-resistant weeds.[12,19] Traits are also known that give resistance to protoporphyrinogen oxidase (PPO)-inhibiting herbicides, and metabolic inactivation systems based on cytochrome P450 and glutathione-*S*-transferase (GST) enzymes could give tolerance to a wide range of herbicides.[37] For example, native P450 enzymes inactivate a range of herbicides, including some auxins and PSII inhibitors, as well as cell division and ALS-inhibiting herbicides. Other options for HR crops are limited until herbicides with new modes of action are available.

5 DEMANDS FOR WEED MANAGEMENT INNOVATIONS

Synthetic herbicides have been a revolutionary weed management technology for agriculture, but now the technology needs to be renewed. Synthetic herbicides with new modes of action have proved to be finite commodities that growers tended to overuse until they lost effectiveness.[19] No weed management tool, not even a herbicide as good as glyphosate, can be used alone and repeatedly over vast areas and remain effective. Agriculture must learn from this experience and avoid the paradigm of overusing any chemical technology until it is no longer effective and then switching to another chemical technology – today there are not enough other chemical technologies.

Synthetic herbicides are still essential for weed management and any new synthetic herbicide with a new mode of action will help greatly to manage weeds, but growers need more alternatives. Weed management practices in HR crops are evolving from using herbicides only back to using herbicides with cultural and mechanical practices. The judicious use of new herbicide options created with the commercialization of new multiple HR crops is essential if the technologies are to stay effective and slow the evolution of HR weeds. However, multiple HR crops will not be the total solution, particularly for key weeds that have the propensity to evolve resistance to multiple herbicide modes of action.

Growers desperately need new technologies and integrated systems to control multiple HR weeds.[45,46] The next new technology to have a large impact on weed management practices may not be a herbicide. Research on allelochemicals, biofumigants, diverse crop rotations, higher seeding rates, intercropping, competitive cultivars and planting patterns, physical weed control, weed seed destruction and reducing weed seed and vegetative promogule dormancy is crucial for a sustainable future.[47]

Fortunately, research has already made some significant progress in some areas. For example, the increased use of bioherbicides shows potential in a number of areas, even for the control of the infamous GR Palmer amaranth,[48] and businesses are making huge investments in the technology.[49] Several new bioherbicides are under development, but current bioherbicides are generally not potent or consistent enough for broad use in commercial crops. Additional research is needed to enhance activity so that more growers can take advantage of their often complex modes of action that make it more difficult for weeds to evolve resistance. Using bioherbicides and synthetic herbicides together could be a very effective resistant weed management practice in the future.[45]

Another biological technology in the early stages of development that has great potential to help manage weeds is the use

Table 3. Updated example of efficacy and herbicide resistance status for selected weed genera likely to occur in herbicide-resistant crops[8]

Weed genus	Efficacy and resistance status[a, b]					
	Glyphosate	Glufosinate	ALS inhibitors	Synthetic auxins	HPPD inhibitors	ACCase inhibitors
Dicotyledons						
Chenopodium	+++R	+++	++R	+++R	+++	
Amaranthus	+++R	+++	+++R	+++R	+++R	
Ambrosia	+++R	+++	+++R	+++	+++	
Conyza	+++R	+++	++R	+++	+++	
Kochia	+++R	+++	+++R	+++R	++	
Monocotyledons						
Setaria	+++	+++	+++R		+++	+++R
Sorghum	+++R	+++	+++R		+++	+++R
Digitaria	+++R	+++	+++R		++	+++R
Echinochloa	+++R	+++	+++R		++	+++R
Lolium	+++R	+++R	+++R			+++R

[a] Weed control ratings are summarized from US extension guides, with +++ representing 80% or higher control possible when a herbicide with that mode of action is applied at optimum timing, ++ represents 60–80% control, + represents 40–60% control and a blank represents no significant control.
[b] An 'R' next to the herbicide efficacy rating indicates that the genus has evolved resistance to that herbicide class.[6]

of RNA interference (RNAi). The technology is an early outcome of functional genomic programs and is in the early stages of development for weed management. The use of RNAi involves the topical application of double-stranded RNA (*ds*RNA) oligonucleotides, typically about 21 base pairs, to interfere with the expression of herbicide resistance genes in weeds.[50] If the genetic basis for resistance can be determined, a *ds*RNA oligonucleotide sequence can be designed to silence the resistance mechanism and make the HR weeds sensitive to the herbicide again. To date, field experiments have demonstrated that the technology can make weeds that are resistant to glyphosate sensitive to glyphosate again. The technology has also been demonstrated with weeds resistant to ALS-, HPPD- and PPO-inhibiting herbicides. RNAi is a potentially revolutionary technology for resistant weed management, but still has a number of very significant technical and regulatory issues that must be addressed before it is commercialized.

Crops also have the potential to improve their competitiveness versus weeds. One such technology in the early stages of research is the genetic engineering of crops to outcompete weeds for essential nutrients. For example, all plants can utilize phosphate (PO_4^{-3}) as a phosphorous source, but none can currently utilize phosphite (PO_3^{-3}). However, some microorganisms can oxidize phosphite to phosphate, and crops genetically engineered with those genes have outcompeted weeds in a fertilization regime with phosphite as a sole phosphorus source, achieving similar productivity to that obtained using phosphate fertilizer and herbicides.[51] If commercialized, this technology could potentially allow growers to fertilize and concomitantly manage weeds without using herbicides.

Historically, the use of economic thresholds in weed management has encouraged leaving a few weeds in fields that cost more to remove than the current year yield benefit from removing them, but the long-term financial impact of HR weeds is changing that philosophy. For better sustainment of currently effective weed management technologies, some are now encouraging growers to control all weeds more aggressively during the growing season and prevent any weeds from setting seed and increasing the weed seedbank. To achieve that level of control, growers must use a high level of chemical, cultural and mechanical weed management practices. The philosophy is termed 'zero tolerance' because it attempts to keep weed levels at zero, well below their short-term economic thresholds for maximum yield. The extra time and expense are justified by taking into account the value of having fewer weed problems in the future, particularly fewer HR weed problems.[52]

Another way to reduce weed populations is to capture or destroy weed seeds at harvest. Four technologies that do this are being used widely in Australia: chaff carts, hay baling, windrow collection and burning and chaff grinders, which collect seed at harvest and mechanically destroy the weed seeds with a cage mill.[53,54] These technologies can prevent over 95% of the weed seeds from reaching the soil seed bank and thus dramatically reduce any HR weed populations in following crops. With fewer weeds exposed to herbicide selection pressure, the chances are proportionately less that weeds will evolve herbicide resistance.

6 OUTLOOK

The need to control rapidly spreading multiple HR weeds is creating a huge demand for new technologies, but, for the near future, growers will need to rely on existing technologies. Experience over the last 30 years has shown that new weed management tools, particularly herbicides with new modes of action, are rare and valuable commodities and, when they become available, need to be stewarded with best management practices so that their utility can be sustained as long as possible. Existing herbicides will continue to be important weed management tools, but the use of herbicides is evolving into more integrated systems with other mechanical, cultural and crop-based weed management technologies.

Many weed scientists now believe that the focus on chemical herbicide weed management has gone too far, particularly when the herbicides are tightly matched with widely used transgenic crops.[47] The time for using a single herbicide to manage weeds is over. Herbicides alone, even when applied in mixtures or sequentially, can only delay the evolution of resistant weeds. New herbicides, particularly any broad-spectrum herbicides with new modes of action, will be essential to control resistant weeds, but herbicides alone will not be the 'silver bullet' or total solution. Growers must use an array of tools to prevent HR weeds from evolving and spreading, with the ultimate goal of not allowing any weeds to survive and set seed.

Researchers are again working hard and making progress discovering new weed management technologies to combat HR weeds.[55] When some of these new technologies become available, growers must not use them alone, as they often did with glyphosate, but must preserve these technologies as long as possible by integrating their use with other weed management technologies from the onset of commercialization. Weeds will eventually evolve resistance to any single weed management practice, no matter how sustainable the technology may appear. The entire agricultural community needs to be vigilant and encourage the implementation of diverse management systems that are essential to ensure that growers will have the cost-effective and sustainable technologies that are needed to combat resistant weeds and meet the long-term needs of a rapidly growing population for food, fibre and fuel.

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