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Review Article

Weed resistance challenges and management under herbicide resistant cropping systems

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ABSTRACT

Over the last six decades, herbicides have been the mainstay of weed management in cropping systems around the world, especially in the Western Hemisphere. A direct consequence of intensive use of herbicides is the development of resistance in weed populations. The extreme popularity of transgenic glyphosate-resistant crops has resulted in resurgence in herbicide resistance issues and further aggravated the situation. The major factors affecting evolution of herbicide resistance in weeds include gene mutation, initial frequency of resistance alleles, inheritance, weed fitness in the presence and absence of herbicide, type of pollination, gene flow, and farming practices that favour a limited number of dominant weed species. As of now, five modes of herbicide resistance have been identified in weeds: target-site mutation, metabolic deactivation, reduced absorption and/or translocation, sequestration, and gene amplification. Integrated and diversified management programs are indispensable in combating herbicide resistance in weed populations.

Key words : Glyphosate resistance, Herbicide resistance, Herbicide-resistant crops, Herbicide-resistant weeds, Integrated weed management, Weed shifts

Over the last six decades, herbicides have been the mainstay of weed management in cropping systems around the world, especially the United States, Canada, Western Europe, and Australia. Other regions such as Southeast Asia and South America have also seen increased use of herbicides in specific crops, for example, rice, wheat, soybean etc. A direct consequence of intensive use of herbicides is the evolution of 'resistance' in weed populations. The rapid adoption of transgenic glyphosate-resistant crops (GRCs) in countries, where they have been commercialised has resulted in an explosion of herbicide resistance issues. The terms "resistance" and "tolerance" are often used inconsistently by weed scientists and non-weed scientists alike. Also, herbicide manufacturers/seed companies who develop and/or market herbicide-resistant crops (HRCs), cultivars/varieties, frequently refer to these as herbicide tolerant entities. The Weed Science Society of America (WSSA) defines herbicide resistance as "the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type." Herbicide resistance in plants may be naturally occurring or induced by such techniques as genetic engineering or selection of variants produced by tissue culture or mutagenesis (WSSA 1998). On the other hand, tolerance is defined as "the inherent ability of a species to survive and reproduce after herbicide treatment." This implies that there was no selection or genetic manipulation to make the plant tolerant; it is naturally tolerant (WSSA 1998).

The primary objective of this review is to summarise herbicide resistance in weeds covering history, worldwide distribution, underlying mechanisms, contributing factors, ecological, economic, and environmental issues, and integrated weed management strategies. The discovery and development, adoption trends, benefits, and consequences of use of HRCs have been reviewed by Reddy and Nandula (2012).

Worldwide Distribution of Herbicide-Resistant Weeds

The most reliable and comprehensive up-to-date database of cases of herbicide resistance in weeds is maintained by Ian Heap (www.weedscience.com). As of 5 April, 2012, there are 376 distinctive cases of documented herbicide resistance in weeds comprising of 203 species (118 dicots and 85 monocots), covering more than 570,000 fields around the world (Heap, 2012). The coun-

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try-wide distribution of herbicide-resistant (HR) weeds is summarized in Table 1. The top five countries with most HR weeds are the US (139), Australia (60), Canada (52), Spain (33), and France (33). The chronological increase in unique cases of herbicide resistance in weed species across the world is depicted in Figure 1. Resistance to herbicides based on herbicide modes of action is represented in Figure 2.

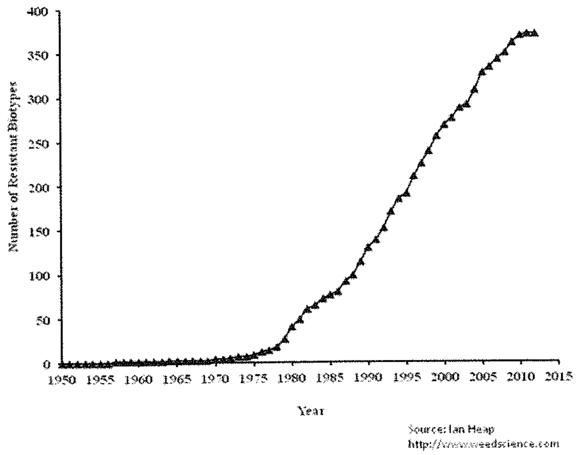

Fig 1. Chronological increase in herbicide resistant weeds worldwide (from Heap, 2012).

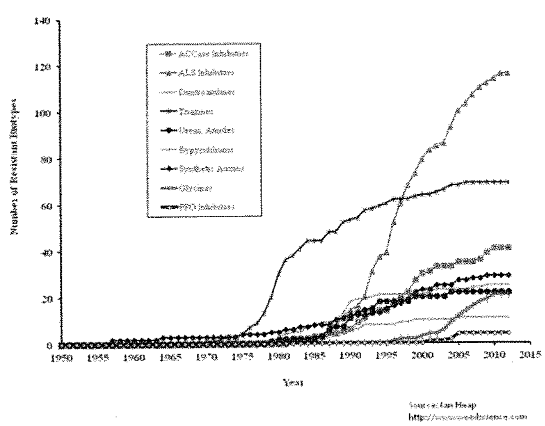

Fig 2. Herbicide resistant weeds worldwide separated by herbicide mode of action (from Heap, 2012).

Several crops [*e.g.,* corn, *Zea mays* L., soybean, *Glycine max* Merr., and cotton *Gossypium hirsutum* L.] developed to be resistant to a number of herbicides (*e.g.,* bromoxynil, glufosinate, glyphosate) by transgenic technology were commercialised in the mid-1990s. Among these, glyphosate resistant crops (GRCs) are the most successful transgenic crops in the world. The unprecedented commercial success of GRCs has increased glyphosate use with a concomitant decrease in the use of other herbicides. Increased intensity of glyphosate use has increased selection pressure to evolve glyphosate-resistant (GR) weeds regardless of cropping systems. The first reported resistance to glyphosate was in a population of rigid ryegrass (*Lolium rigidum* Gaud.) from an orchard in Australia following repeated applications of glyphoaste for 15 years (Powles *et al.,* 1998). In GRCs, horseweed (*Conyza canadensis* (L.) Cronq.) was the first weed to evolve resistance to glyphosate within 3 years of application (VanGessel, 2001). By 2005, a total of 22 weed species were reported to have developed resistance to glyphosate (Nandula *et al.,* 2005); 14 of these species were in GRCs. Since then, eight more weed species have developed resistance to glyphosate in GRCs. Thus, there is a high selection pressure for the evolution of GR weeds in GR cropping systems.

Factors Influencing Development of Herbicide Resistance

Herbicide resistance development in weeds is an evolutionary process. The factors affecting evolution of herbicide resistance in weeds include gene mutation, initial frequency of resistance alleles, inheritance, weed fitness in the presence and absence of herbicide, pollination type, gene flow, and farming practices that favor a limited number of dominant weed species (Jasieniuk *et al.,* 1996; Owen, 2001; Thill and Lemerle, 2001). When weed densities are high, chances of resistance selection are high, despite a low mutation rate. Soon after the incidence of a resistant plant, continued application of herbicides with identical mechanism of action will increase resistant population. For a given herbicide pressure, the initial frequency of resistance alleles establishes the required number of generations to reach a specific resistance rate. When herbicide selection pressure is weak, the initial frequency of resistance alleles in a population determines the nature and scope of resistance development in a weed population. In randomly mating or cross pollinating species, the frequency of dominant resistance alleles is greater than recessive forms of the resistant gene. However, the frequency of dominant and recessive alleles is nearly the same in self pollinating weed species. Gene flow can occur via pollen, or vegetative propagules (in case of perennial weeds). Rates of gene flow are generally higher than rates of mutation.

Herbicide Resistance Mechanisms

Understanding the processes and means by which weeds withstand labeled herbicide treatments is important for devising effective herbicide resistance management strategies. Currently, five mechanisms of herbicide resistance have been identified in weeds: (1) altered target site due to a mutation at the site of herbicide action resulting in complete or partial lack of inhibition, e.g., most cases of weeds resistant to triazines, acetolactate synthase inhibitors, and acetylCoA carboxylase inhibitors, and goosegrass (*Eleusine indica* L.) resistance to glyphosate; (2) metabolic deactivation, whereby the herbicide active ingredient is transformed to non-phytotoxic metabolites, e.g., multiple resistant rigid ryegrass biotypes from Australia; (3) reduced absorption and/or translocation that results in restricted movement of lethal levels of herbicide to point/site of action, e.g., Italian ryegrass [*Lolium perenne* L ssp. multiflorum (Lam.) Husnot] resistance to glyphosate; (4) sequestration/compartmentation by which a herbicide is immobilized away from the site of action in locales such as vacuoles or cell walls, e.g., horseweed resistance to glyphosate; and (5) gene amplification/overexpression of the target site with consequent dilution of the herbicide in relation to the target site, *e.g., Palmer amaranth* (*Amaranthus palmeri* (S.) Wats.) resistance to glyphosate.

Weed Shifts

Crop production over the last 100 years has involved intensive inputs such as mechanical equipment, fertilisers, crop protection chemicals, and fuel. A major consequence of this 'disturbed' agro-edaphic environment with regards to weed management has been a change in the weed spectrum as well as biodiversity in the cropping environment. Such a change is defined as 'weed species shift'. A weed species shift can be from season to season in response to continual disturbance (fluctuational) or a continuation of weed emergence towards composition stability over time after a disturbance (successional) (Swanton *et al.,* 1993). An additional challenge faced by land managers is the development of herbicide resistance in weed species that have newly occupied a niche, in hitherto, nonexistent habitats. For example, *Conyza* spp. traditionally occurs in areas such as orchards, roadsides, vineyards, hay crops, pastures, and rangelands. However, with widespread adoption of GR crops and associated glyphosate use, *Conyza* species have moved to agronomic field crops such as corn, soybean, and cotton, and have developed resistance to glyphosate. The following discussion of weed shifts is limited to research conducted in the US.

A 6-yr (1998 through 2003) field study was conducted in Nebraska, US, to measure weed shifts following multiple applications of two rates of glyphosate or alternating glyphosate with non-glyphosate treatments in continuous GR corn or in a crop rotation of corn sugarbeet (*Beta vulgaris* L.), and spring wheat (*Triticum aestivum* L.) with all three crops resistant to glyphosate (Wilson *et al.,* 2007). After 6 yr, plant densities of common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), hairy nightshade (*Solanum physafolium* Rusby), and common purslane (*Portulaca oleracea* L.) increased in the corn-sugarbeet-spring wheat crop rotation compared with continuous corn. An experiment conducted in South Carolina, US, from 2001 to 2005 to determine the impact of no-till and GR corn and soybean, involving glyphosate-only and non-glyphosate programs, on changes in the weed composition indicated a rapid shift in weed species, especially, that in perennial weeds (Norsworthy, 2008). Perennial weeds represented 10% of the total weed biomass in 2001, but increased to 99% by 2004 in non-glyphosate systems regardless of tillage. Summer annual grasses declined from 20% in 2001 to <1% in 2002 and 2004, based on total weed biomass. Further, the seed density of most species declined over the four cropping years. The most recent problematic weeds in cropping systems have been annual broadleaf weeds (Johnson *et al.,* 2009).

Twelve weed scientists in 11 states responded to a survey across the US, conducted to address weed shifts in GR corn, cotton, and soybean (Culpepper, 2006). Weed shifts did not occur in GR corn, but were observed in GR cotton and soybean. In GR cotton, Amaranthus, Commelina, Ipomoea, and *Cyperus* species as well as annual grasses were more problematic. In GR soybean, various winter annuals, lambsquarters species (*Chenopodium* spp.), and waterhemp species were more abundant in addition to Ipomoea and Commelina. All weed scientists believed that weed shifts were taking place and two-thirds of them observed these were of economic importance. The compositions of the germinable weed seedbank and aboveground weed communities in a long-term tillage and rotation study indicated that a shift to GR corn and soybean cropping did not significantly change the weed seedbank makeup in a short term of 4-6 yr (Sosnoskie *et al.,* 2009). The sole reliance on GR cotton in Georgia, US, has caused a naturally-tolerant species, Benghal dayflower (*Commelina benghalensis* L.), to spread across the state (Webster and Sosnoskie, 2010). In addition, monoculture of GR cotton in Georgia helped create the biggest weed problem in the southern US, GR Palmer amaranth.

The Southern Weed Science Society in the US conducts annual surveys on weed species occurrence and abundance in various cropping systems. An analysis of these surveys was carried out to document changes in the weed spectrum of the southern US since the introduction of HR crops in the mid 1990's (Webster and Nichols, 2012). In 1994 and 2009, the most troublesome weeds in corn, cotton, and soybean were morningglories (*Ipomoea* spp.), Texas millet (*Urochloa texana* (Buckl.) R. Webster), broadleaf signalgrass (*Urochloa platyphylla* (Nash) R. D. Webster), johnsongrass (*Sorghum halepense* L.), sicklepod (*Senna obtusifolia* (L.) H. S. Irwin & Barneby), and nutsedges (*Cyperus* spp.). In 2009, GR Palmer amaranth and horseweed were the second and fourth most troublesome weeds of soybean. In wheat, the top four troublesome weeds were *Italian ryegrass*, wild garlic (*Allium vineale* L.), wild radish (Raphanus raphanistrum L.), and henbit (*Lamium amplexicaule* L.) in 1994 and 2008. The widespread use of glyphosate was one of the main causes for the observed changes in weed flora. An integrated weed management program is needed to prevent and/or delay shifting weed spectrums and sustaining HR crops in the long term (Reddy and Norsworthy, 2010).

Some Aspects of Herbicide-Resistant Weeds

Economic issues

Herbicide-resistant weeds affect crop production by delaying planting, tillage, harvesting, and other production operations in between, increasing weed management costs both in the short- and long-term, and by reducing crop yield both quantitatively and qualitatively. It was estimated that the yield loss in soybeans was \$108 and \$130/ha due to competition from acetolactate synthase inhibitor resistant common ragweed (*Ambrosia artemisiifolia* L.) and redroot pigweed, respectively, both at a density of 2 plants/m^2 (Cowbrough, 2002). Four GR volunteer corn plants per m^2 reduced soybean yield value by \$97/ha. Glyphosate-resistant johnsongrass in soybean cost Argentine farmers an additional \$31.2/ha/yr (Papa *et al.*, 2005). Glyphosate-resistant horseweed reduced up to 70% of soybean yield in Brazil, depending on weed density (Gazziero *et al.*, 2010). These are just a few examples of the yield reduction potential of HR weeds. A comprehensive report on estimated increased costs associated with the control of GR weeds in corn/maize, cotton, and/or soybean in the US is provided in Table 2 (Carpenter and Gianessi, 2010). Additionally, HR weeds are most likely to negate any environmental advantages (Reddy and Nandula, 2012) gained from the commercialisation of HR crops.

Gene flow

The transfer of herbicide resistance traits from resistant to susceptible weed populations can occur via pollen or seed, and in addition, via vegetative propagules in perennial species. The classic examples of HR gene flow via pollen in recent times include GR pigweeds (Palmer amaranth and tall waterhemp (*Amaranthus tuberculatus* (Moq.) Sauer) and *Lolium* spp. (rigid and Italian ryegrasses). These weed species are characterised by high genetic variability among populations and can interbreed between species within the *Amaranthus* or *Lolium* genus. Further, some of these species are prolific seed producers. For example, a single Palmer amaranth female plant can produce up to 1.8 million seeds (Ken Smith, University of Arkansas, unpublished data) and a horseweed plant can generate 72,000 (Davis and Johnson, 2008) to 200,000 seeds per plant (Shields *et al.*, 2006). Another attribute of horseweed aiding in gene flow over a long distance is the ability of wind-borne seeds to travel up to 500 km in a single dispersal event (Shields *et al.*, 2006).

Fitness

Fitness can be defined as the ability of a resistant biotype or population to survive and reproduce in an environment that may or may not include an herbicide application. Fitness issues of HR weeds came to the fore with the discovery of triazine-resistant weeds. The triazine family of herbicides inhibit the photosystem II in susceptible/wild type weed populations. Triazine-resistant weeds began to appear a few years after the initial applications. Several resistant populations were found to have reduced photosynthetic rates, concomitant reduction in growth and vigor, and/or fecundity compared with their susceptible counterparts in the absence of 'selection pressure' (the effective-

Table 1. Worldwide distribution of herbicide-resistant weeds.

Country	Number of resistant weeds	Country	Number of resistant weeds
Argentina	8	Italy	19
Australia	61	Japan	18
Austria	2	Kenya	1
Belgium	18	Malaysia	17
Bolivia	7	Mexico	5
Brazil	26	New Zealand	10
Bulgaria	4	Nicaragua	1
Canada	53	Norway	5
Chile	14	Panama	1
China	15	Paraguay	2
Colombia	6	Philippines	3
Costa Rica	5	Poland	10
Czech Republic	16	Portugal	3
Denmark	3	Saudi Arabia	1
Ecuador	1	Slovenia	1
Egypt	1	South Africa	14
El Salvador	1	South Korea	12
Ethiopia	1	Spain	33
Fiji	1	Sri Lanka	2
France	33	Sweden	2
Germany	26	Switzerland	14
Greece	7	Taiwan	1
Guatemala	1	Thailand	5
Honduras	1	The Netherlands	7
Hungary	1	Tunisia	1
India	3	Turkey	14
Indonesia	1	United Kingdom	24
Iran	11	USA	139
Ireland	1	Venezuela	9
Israel	27	Yugoslavia	6

Adapted from Heap (2012).

ness of a herbicide in altering the genetic composition of a population over a series of generations) from triazine herbicides. The mechanism of resistance to the triazine herbicides was elucidated, in most cases, to be due to a point mutation on the D1 protein. While triazine resistant weeds created an initial interest about the negative impact of resistance on crop production, further research was not initiated due to lack of fitness of resistant individuals. This resulted in their inability to compete with crop plants and cause significant impact on yield. However, weeds resistant to acetolactate synthase inhibitors, acetyl-CoA carboxylase inhibitors, auxin-type inhibitors, and glyphosate did not have fitness considerations, for the most part.

Management of Herbicide Resistance in Weed Populations

Weed management programs must not be solely dependent on herbicides in order to be economically sustainable in the long term. In general, a combination of the following strategies is recommended for managing HR weeds:

Residual herbicides

Residual herbicides can be applied preplant incorporated, pre-emergence, early post-emergence and late post emergence. In the case of cotton, directed post emergence applications are also recommended. Residual herbicides are dependent on moisture availability in the soil for 'activation', either through rainfall or irrigation. However, the benefits from HR weed management far outweigh the unpredictability associated with residual herbicides. Herbicide manufacturers, distributors, as well as contract crop management companies are offering incentives and stewardship programs when residual herbicides are included in a weed management program. Residual herbicides offer a broad spectrum of weed control, reduce pressure from winter annuals that have emerged the previous fall and possess an established root system heading into spring planting, and an alternative mode of herbicide action that helps prevent or delay resistance development.

Crop rotation

Crop rotation is a trusted and time-tested strategy that has been in vogue for several decades. The main objective of rotating crops is the removal of the host plant, i.e. crop, harbouring diseases and pests. Also, the lifecycle of weed species that are associated with the crop is disrupted. Although GR crops are rotated with each other, the basic weed management tool remains to be glyphoste. It is recommended to rotate GR crops with conventional or non transgenic crops that would add diversity in herbicide applications as well as interrupt the growth cycle of HR weeds or weeds prone to develop herbicide resistance. If economic reasons dictate rotating HR crops with similar technology, utilizing one or more of the other strategies such as residual herbicides is recommended.

Rotate herbicides with different modes of action

Application of herbicides with alternative mode of action has several advantages such as the control of weeds resistant to a particular herbicide or herbicide mode of action, a broader spectrum of weed control, and a competitive advantage provided to the crop over later emerging weeds. An added benefit would be the prolonged sustainability of glyphosate, other herbicides, and HR crop technology. These gains from rotation of herbicide chemistries are significant in the light of lack of new herbicide modes of action. The last new herbicide mode of action, inhibition of hydroxyphenyl pyruvate dioxygenase, was commercially introduced almost 20 years ago. It is expected that given the widespread problem of herbicide resistance in weeds, the agro-chemical companies would re-focus their efforts towards discovering new herbicide modes of action.

Tank-mix herbicides with different modes of action at full recommended rates

A common practice followed by growers around the world is the application of less than labeled rates of herbicides as a cost saving strategy. Herbicides should always be applied at the full recommended rates, whether applied alone or in tank-mix combinations. It was generally understood among the scientific community and recently proven in the case of rigid ryegrass (Manalil et al. 2011), that repeated application of herbicides at low doses causes rapid evolution of herbicide resistance. Of course, the rate of resistance development dependents on the genetics of the targeted weed, specificity of herbicide action, and the prevailing conditions at the time of herbicide application.

Avoid repeated applications of the same herbicide

Application of same herbicide or herbicides with a similar mode of action multiple times in a growing season or consecutive seasons on a single field will most definitely promote and enhance the development of herbicide resistance in intended weed populations by increasing the selection pressure. Therefore, choice of residual herbicide or herbicides with alternative modes of action, via crop rotation or rotation of herbicide chemistry, should be carefully made to delay resistance development or avoid weed shifts.

Utilize tillage, cultivation, and other cultural practices wherever and whenever feasible

The introduction of the acetolactate synthase inhibiting herbicides in the late 1980s and early 1990s revolutionised weed management in row sown crops. These herbicides were characterized by low dosages, highly specific mode of action, broad weed spectrum, and benign environmental properties. As a consequence, they were readily accepted by growers and no-till agriculture began to be increasingly popular. The heavy cultivation equipment was done away with. The introduction of GR crops in the 1990s followed by their unprecedented acceptance further promoted no-till crop production given the benefits of fuel savings and less soil erosion from reduced disturbance of soil. Weeds that were susceptible to cultivation, especially, small seeded grasses and broadleaf species, began to thrive under no-till conditions. Thereafter, some of these weed species developed resistance to herbicides, thereby, further exacerbating their management. Selective tillage is being considered in the US as well as other parts of the world where infestations of HR weeds are heavy. 'Hand weeding' of GR Palmer amaranth is currently being practiced in Georgia and other states in the southern US, costing up to $250/ha (Stanley Culpepper, University of Georgia, personal communication). Italian ryegrass populations reduce land value by impacting conservation practices. Some land managers have renewed a call for tillage in the fall to control HR Italian ryegrass in southern US, but this practice is contrary to the mission of the Natural Resources Conservation Service and has drawn their attention.

Table 2. Estimates of increased costs associated with control of glyphosate resistant weeds in the United States.

State	Crop	Weed	Increased cost/acre
Arkansas	Cotton	Palmer amaranth	$14.07-35
Delaware	Soybean	Horseweed	$3-12
Georgia	Cotton	Palmer amaranth	$3-100
Illinois	Soybean	Common waterhemp	$35.82
	Corn	Common waterhemp	$0
Minnesota	Corn	Common waterhemp and giant ragweed	$0
	Soybean	Common waterhemp and giant ragweed	Equal or slightly lower
Mississippi	Soybean	Horseweed	$8.40-15.50
		Italian ryegrass	$10.85-20.45
		Palmer amaranth	$6.01-11.00
	Corn	Horseweed	$1.82-16.00
		Italian ryegrass	$4.20-21.96
		Palmer amaranth	$1.82-35.02
	Cotton	Horseweed	$5.44-15.41
		Italian ryegrass	$14.52-26.50
		Palmer amaranth	$6.19-20.44
Missouri	Soybean	Common ragweed	$20-25
	Soybean	Common waterhamp	$20-25
	Corn	Common waterhemp	$0-15
	Cotton	Horseweed	$5
New Jersey	Soybean	Horseweed	$3-12
North Carolina	Cotton	Horseweed	$10
	Corn	Palmer amaranth	$13
	Cotton	Palmer amaranth	$15-40
	Soybean	Palmer amaranth	$19
	Soybean	Horseweed	$10
South Carolina	Cotton	Palmer amaranth	$25-50
Tennessee	Cotton	Giant ragweed	$16
	Soybean	Giant ragweed	$30
	Cotton	Horseweed	$20
	Soybean	Horseweed	$13-23
	Cotton	Palmer amaranth	$30-33
	Soybean	Palmer amaranth	$32-42
	Cotton	Horseweed	$25.49
	Soybean	Horseweed	$11.51
	Corn	Horseweed	$0

Adapted from Carpenter and Gianessi (2010) and modified.

Note: Costs include application costs where appropriate if herbicides are applied separately from glyphosate application and may also include costs of cultivation or hand weeding.

Clean equipment thoroughly before and after each use

Farm equipment such as tractors, planters, sprayers, and combines have changed rapidly over the years and are scientifically advanced using latest technology, such as, Global Positioning System, Geographic Information Systems, and precision farming tools. However, modern farm machinery comes with a hefty price. In general, it is unlikely that a single grower would have possession of all such equipment. Further, the number of growers is dwindling globally, with the younger generation seeking lucrative urban and non-agricultural employment. As a consequence, the average farm size has increased in the US and South America. Managing an expansive farm operation requires growers and land managers to hire custom spraying and harvesting services. In addition, borrowing a piece of equipment from a neighbor or helping out a neighbor in completing certain farm operations involves movement of tools from one area to another. Movement of equipment from a field infested with HR weeds can easily introduce a HR weed to a, hitherto, clean field if the equipment is not thoroughly sanitized before entry in to the new field.

Control weeds postharvest to reduce soil seedbank

Growers, in general, address weed management issues, including herbicide resistance, reactively rather than proactively. The reactive approach is often more expensive than the proactive approach. It was estimated that it would cost Mid-South cotton growers in the US $13 for incorporating residual herbicides to help delay the onset of glyphosate resistance in Palmer amaranth in GR cotton compared with an increase of $35/acre for a program that would control an established problem with GR Palmer amaranth (Bryant, 2007). Additionally, the ease and timely weed control obtained from growing GR crops has given growers a false sense of security. After harvest, the usual practice in the US is minimal land preparation for the next growing season or coming back with a preplant burndown application of a non selective herbicide such as glyphosate or paraquat before or at planting the following spring. Post harvest, summer annual weeds such as Palmer amaranth can go through a complete growth cycle and set seed given the short day length conditions in the fall that promote flowering. When left unmanaged, such weeds add to the seed bank creating an abundant supply of seed that could pose a management problem in the next season. Therefore, post harvest weed control is a must to achieve a sustainable farming operation.

CONCLUSIONS

Herbicide-resistant weed(s) management recommendations can be summarised in three words, DIVERSIFY, DIVERSIFY, DIVERSIFY. According to Stephen Powles, the world renowned expert on herbicide resistance from Australia, if a weed management program that most likely includes herbicides is working, it is prudent to change to a more diverse portfolio of control strategies! As herbicides will remain as the dominant method of weed control and HRCs will remain popular among farmers, it is anticipated that HR populations of several other weed species will evolve over time. Evolved HR weeds are a major threat to sustainability of herbicides as well as HRCs. However, herbicide-resistant weeds are not yet a problem in many parts of the world, especially, where HRCs are not commercialized. Lessons can be learnt and proactive action taken to reduce selection pressure to prevent and or delay evolution of HR weeds. The effective strategy to manage herbicide resistance in weeds must be based on the concept of diversity. The diversity can be achieved by using a combination of chemical (herbicides with different mechanisms of action, mixtures, sequences), mechanical (preplant tillage, in-crop cultivation, post harvest tillage), and cultural (competitive cultivars, crop rotation, plant density, row spacing, planting date, cover crops) tactics.

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