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Herbicide-resistant weeds: Management strategies and upcoming technologies

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ABSTRACT

Herbicides have contributed to substantial increase in crop yields over the past seven decades. Over reliance on herbicides for weed control has led to rapid evolution of herbicide-resistant (HR) weeds. Increased awareness of herbicide resistance and adoption of diversified weed control tactics by farmers is critical to manage HR weeds. HR weed management must include both chemical and non-chemical methods as well as the best management practices to prevent evolution and spread of HR weeds. The severity of the HR weed problem has also renewed efforts to discover new technologies. One technology will be a new generation of crops with resistance to glyphosate, glufosinate and other existing herbicides (*e.g.* ALS inhibitors, 2,4-D, dicamba, HPPD inhibitors, and ACCase inhibitors). These stacked-trait crops will provide new options with existing herbicides, but will not be the total weed management solution because several weeds have already evolved resistance to these herbicides. Another technology in the early stages of development that has potential to combat HR weeds is the use of RNA interference (RNAi) technology. The use of RNAi involves the topical application of double-stranded RNA (dsRNA) to interfere with the expression of herbicide resistance genes in weeds to reverse the resistance. RNAi is a revolutionary technology for resistant weed management, but is still years away from commercialization. While no new herbicides are on the horizon, in the near future, the HR management strategies must utilize an array of tools to disrupt HR weeds from evolving and spreading, with the ultimate goal of not allowing any weeds to survive and set seed.

Key words: Herbicide-resistant weeds, Management strategies, Upcoming technologies

Weeds have been with us since time immemorial and are not likely to disappear, despite the use of best weed management practices. Weeds interfere with profitable production of food, feed, fiber, and fuel crops. Development of safe, effective, and relatively inexpensive herbicides coupled with advances in application technology during the past seven decades have provided many successful weed control options in crop production. Efficient and judicious use of herbicides contributed to not only higher crop yields, but also, improved quality. Furthermore, herbicides, reduced labor and drudgery, use of animal drawn implements, machinery, and fuel used for mechanical weed control. Without a doubt, herbicides provided cost-effective, timely weed control and have helped producers become highly productive and remain economically viable.

The era of chemical weed control began with the introduction of 2,4-D in mid-1940s. Since then, we have witnessed development of a wide array of herbicides, ever more specific and more active. Currently, over 270 herbicides acting at 25 different primary target sites are on the market. Use of each herbicide although is limited to a specific situation, herbicides have greatly expanded pre-emergence and post-emergence weed control options in both crop and non-crop lands. It is now difficult to imagine modern crop production without the use of herbicides.

Herbicide use increased more than thirteen-fold (from16 to 217 million kg) between 1960 and 1981 as more U.S. farmers began to treat their fields with these chemicals. By 1980, more than 90-99% of the U.S. corn, cotton, and soybean area was treated with herbicides as compared to 5-10% of area planted in 1952 (Fernandez-Cornejo *et al.* 2014). Over reliance on herbicides for weed control has led to rapid evolution of herbicide-resistant (HR) weeds. The most common cause of evolution of resistant weeds is by exerting selection pressure on weeds with the use of same herbicide (or herbicides with the same target site of action) year after year. Herbicide resistance was first reported in 1970 in triazine chemical family (Heap 2016). Since that time, several weed species have evolved resistance to not only triazine herbicides, but also, to herbicides with different target sites of action. As of 2015, globally,

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248 weed species (104 monocots and 144 dicots) have evolved resistance to 157 herbicides representing 22 of the 25 known herbicide sites of action in 86 crops in 66 countries (Heap 2016).

Herbicide-resistant crops (HRCs), mainly glyphosate- and glufosinate-resistant soybean, corn, cotton, and canola were commercialized in the mid-1990s. The consistent weed control and economic benefits of HRCs encouraged the farmers to plant more area with HRCs each year in countries where adopted. In the US, 94% of soybean, 89% of cotton, and 89% of corn area was planted with glyphosate-resistant (GR) cultivars in 2015 (USDA 2016). Globally, 82% of soybean, 68% of cotton, and 30% of corn area was planted with GR cultivars in 2014. The remarkable success of GR crops has increased glyphosate use, consequently, increasing selection pressure that resulted in widespread evolution of GR weeds. As of 2015, globally, 32 weeds have developed resistance to glyphosate (Heap 2016). Once an effective weed control tool, glyphosate is now unreliable. Glyphosate has become a victim of its own success – used too often on same area with no diversity in weed management. Efficacy of glyphosate is declining as more weeds develop resistance. GR weeds can reduce crop yields and increase weed management costs (Culpepper *et al*. 2008, Webster and Sosnoskie 2010, Shaw *et al*. 2011).

Herbicide-resistant weed management with diverse approaches

After years of heavy dependence on a single solution to weed control, glyphosate-resistant crops and glyphosate herbicide system have become ineffective. Herbicide resistance is choice-driven. Users will either promote or prevent by the weed control choices they make. Herbicide dependence strategy has failed. Change is essential. Growers must change weed control practices.

Herbicides are still essential for weed management in modern cropping systems. Increased awareness of herbicide resistance and adoption of diversified weed control tactics by farmers is critical to manage HR weeds. HR weed management must include use of cultural (competitive cultivars, plant densities, row spacing, crop rotation, winter crops in rotation, cover crops), mechanical (tillage before planting, in-crop cultivation, hand hoeing, post-harvest tillage), chemical (residual herbicides, herbicide full-labelled rate, tank mixtures at the label rate, sequences, application timing, herbicide rotation with different modes of action), and biological tactics where and when available, for effective weed control (Nandula and Reddy 2012, Reddy and Nandula 2012). These practices were commonly used for weed control prior to herbicides. Growers were complacent, because herbicides simplified weed control and increased profitability.

Other management practices include use of weed-free crop seed, keeping fields weed-free, preventing within field and between fields movement of weed seed, and understanding the biology of the weeds and use of diversified weed management approaches to prevent weed seed production and depletion of weed seed in the soil seedbank. Norsworthy *et al.* (2012) have published a document on risks of herbicide resistance and suggested several best management practices and recommendations for herbicide-resistance management.

Herbicides are the primary and economical means of weed management in crop production. Any diversification of control tactics will no doubt increase cost of weed management in the short-term. Because of increased short-term costs associated with the use of diverse weed control tactics, growers are often hesitant to adopt proactive measures to manage HR weeds. Ignoring HR weeds now will only make herbicide resistance problem severe and expensive to manage later. Considering that the discovery of herbicides with new modes of action is rare, the indiscriminate use of current herbicides will lead to rapid evolution of more HR weeds resulting in loss of herbicides for future use. Integration of herbicides with non-chemical weed control tactics is critical to conserve herbicides resources for the future. Thus, the short-term costs associated with diverse weed control tactics are pale in comparison to long-term consequences.

Evolution and widespread infestation of GR Palmer amaranth (*Amaranthus palmeri*) in Georgia, USA, cotton weed management has moved from use of glyphosate only herbicide to diversified tactics (Sosnoskie and Culpepper 2014). In order to manage GR Palmer amaranth, growers are rotating herbicide chemistries and limiting their reliance on a single mechanism of action, and are applying residual herbicides throughout the cropping season, and integrating herbicide programs with hand weeding, tillage for incorporation of preplant herbicides, in-crop cultivation, post-harvest deep tillage once in three years to manage weeds. Consequently, these systems were more diverse, complex, and expensive than those used only a decade ago, but are effective in controlling GR Palmer amaranth in GR cotton.

Early detection

Aside from using an array of weed control tactics in HR weed management, early detection of resistant weeds is critical. Resistant weeds go undetected until growers observe about 30 percent weed control failure for a particular weed species. Early detection of resistant weeds is critical to avoid the spread of the resistant weed biotype. Unfortunately, resistant and susceptible plants look alike and resistance is not detected until the susceptible plants are killed and the herbicide-resistant plants survive following exposure to a dose of herbicide that would normally be lethal to the susceptible plants. If these resistant weeds are detected early, before their populations increase, growers can employ diverse weed management tactics that can prevent their spread.

New multiple herbicide-resistant crops

Agrochemical industries reduced research spending during the years glyphosate dominated the herbicide market. The discovery and development of a new compound is expensive, and the new product must exceed the high bar set by glyphosate. As a result, there are a fewer new herbicides under development.

The severity of the HR weed problem has also renewed efforts to discover new technologies. One technology will be a new generation of crops with resistance to glyphosate, glufosinate and other existing herbicides. Currently, Monsanto, Dow, Bayer, Syngenta and BASF are developing new stacked-trait crops in combination with glyphosate resistance. They are glyphosate, glufosinate (soybean, corn, cotton); glyphosate, ALS inhibitors (soybean, corn, canola); glyphosate, glufosinate, 2,4-D (soybean, cotton); glyphosate, glufosinate, dicamba (soybean, corn, cotton); glyphosate, glufosinate, HPPD inhibitors (soybean and cotton); glyphosate, glufosinate, 2,4-D, ACCase inhibitors (corn); and glufosinate, dicamba (wheat) (Green 2014). These stacked-trait crops will provide new options with existing herbicides, but will not be the total weed management solution because several weeds have already evolved resistance to these herbicides (Heap 2016).

RNA interference technology

Another technology in the early stages of development that has potential to combat HR weeds is the use of RNA interference (RNAi) technology. Monsanto is developing RNAi technology (BioDirect™); mechanism called RNA interference or gene silencing. It's a way to destroy specific RNA messages so that a particular protein is not made. It's an elegant way of targeting particular genes and turning those genes off. The use of RNAi involves the topical application of a mixture of glyphosate and double-stranded RNA (dsRNA) to interfere with the expression of herbicide resistance genes in weeds. Preliminary studies have demonstrated that BioDirect™, when combined with herbicide, can reverse the resistance. The technology has also been demonstrated with weeds resistant to ALS-, HPPD- and PPO-inhibiting herbicides (Green 2014, Shaner and Beckie 2014). Commercial success of genetic sprays depends on: spray getting into plant cells (uptake), shelf life of formulation, and integrity of formulation in extreme summer hot conditions. RNAi is a revolutionary technology for resistant weed management, but is still years away from commercialization.

Conclusion

While no new herbicides are on the horizon, in the near future, the HR management strategies must utilize an array of tools to disrupt HR weeds from evolving and spreading, with the ultimate goal of not allowing any weeds to survive and set seed. Simple and convenient, herbicide only strategy, has failed and growers must diversify both chemical and non-chemical tactics to manage HR weeds. Growers must and should bring diversity back. The future weed management tactics look lot more like the ones used in the past – the pre-GR crop era. HR weeds are here to stay and growers have to just manage them following two rules. Rule # 1: diversify weed management approaches using an array of control (cultural, mechanical, chemical, and biological) tactics to disrupt HR weeds from evolving and spreading. Since one size seldom fits all, diversified approaches must match local/region specific weed problems. Rule # 2: never forget the Rule #1.

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