Weed Science 2015 63:972–975

Industry Views of Monitoring and Mitigation of Herbicide Resistance

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Managing the risk of herbicide resistance (HR) is strategically important to leading herbicide technology providers and is the focus of the Global Herbicide Resistance Action Committee (HRAC), an organization with representation from 8 major companies, working as a part of CropLife International (Brussels, Belgium). Early detection of HR, understanding the extent of HR in a defined area, and mitigation of resistance through efforts to limit its spread are important aspects of managing HR. Monitoring for HR populations has been employed by weed scientists for both early detection and to define the extent of resistance (Baumgartner et al. 1999; Beckie et al. 2013; Davis et al. 2008; Falk et al. 2005; Owen et al. 2007). Methods used to monitor for resistance have included random or nonrandom seed sample collection from fields, followed by resistance bioassay (field surveys); market research surveys of farmers and weed management experts; and tracking farmer performance inquiries, followed by appropriate field evaluation and testing. Each method has advantages and disadvantages in costs, accuracy, and effectiveness to address HR management goals. Before embarking on a resistance-monitoring program, the objectives, probability of achieving those objectives, and the associated resource needs should be carefully considered. Based on a review of existing monitoring studies and company experiences, HRAC offers the following considerations for herbicide resistance monitoring:

1. Monitoring HR using *qualitative* field survey or market research approaches can be useful to understand and enhance awareness of the scope of the problem and to improve adoption of HR best management practices (BMPs).

   Field monitoring studies have, to date, primarily been conducted using qualitative measurements methods, that involve the collection and testing of seed from plants surviving a herbicide application across a geographic region after resistance has been identified in an area. These studies have been helpful to understand the scope of resistance, to correlate farming practices with the occurrence of resistance (Hanson et al. 2009; Légère et al. 2000) and, at a more-academic level, to understand the relative abundance of different resistance mechanisms.

   There are a number of examples in which market research companies, university extension services, crop protection companies, or others surveyed farmers regarding the presence of resistance on their farms (Foresman and Glasgow 2008; Givens et al. 2011; Zhou et al. 2015). This method provides a general understanding of resistant weed infestations, particularly in geographic areas in which resistance has become established, and there is a common understanding of the problem among farmers. However, farmer surveys are often a reflection of perceptions, rather than facts (Bourgeois et al. 1997). Resistance can often be confused with other causes of poor performance, leading to overestimates of resistance (Amason 2013). A 2007 market survey by Monsanto (St. Louis, MO) found that a significant number of farmers believed they had glyphosate resistance that had not yet been confirmed (MJ Horak, personal communications). Surveys of weed management experts, such as university and extension services and consultants, among others, avoid some bias, but the extent of HR can still be somewhat exaggerated because these individuals tend to work more with farmers that have weed-management problems than they do with those who do not have such problems. Thus, market-research surveys are useful for gaining a qualitative understanding of resistance progression, understanding farmers' perceptions, and raising awareness of the issue.

2. Broad, routine monitoring to *quantify* HR (i.e., documenting the number of acres infested with resistant populations) is not necessary to meet the primary goal of encouraging greater farmer adoption of HR BMPs nor is it a cost-effective use of limited public and private resources.

   To quantify existing resistance in a defined area, random sampling of a large number of fields

DOI: 10.1614/WS-D-15-00101.1

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and plants within a field are required to develop statistically valid results (Beckie et al. 2000). In general, conducting field-monitoring studies to *qualitatively* estimate the level of HR (i.e., low, moderate, or high) can be more cost effective for determining the extent of resistance and, thus, can be more readily justified than monitoring to *quantify* HR in area (i.e., acres or hectares) infested.

3. Random monitoring to detect resistance in a new species or for known resistant species in a new geography before its spread (proactive monitoring) has a low probability of success and is a resource-intensive activity.

   Proactive monitoring can be used to detect resistance before it becomes dominant in a single field or more widespread across a geography. In theory, this type of monitoring could be of value in slowing the selection, development, and spread of resistance. However, a proactive monitoring program must address two critical research challenges: (1) Can practical sampling schemes (i.e., number of individuals, sites, and frequency) with a reasonable probability of detecting rare, resistant individuals be resourced? and (2) Can testing programs actually detect resistant biotypes before resistance becomes broadly established in a field or localized geography. The number of samples required to detect resistance within a weed population in which none has been previously observed will be determined by the estimated frequency of the resistance alleles. From previous experience, these range from 10^{-4} to 10^{-12} or lower for some herbicide sites of action (Duke and Powles 2009; Jander et al. 2003; Neve et al. 2011; Powles et al. 1996). In short, for many herbicides, including glyphosate and the auxins, this would be like "looking for a needle in a haystack." This approach would require extensive field sampling and testing because there is significant genetic variation within and among weed populations in many species. In addition, in cases in which the expression of resistance is multigenic, which may be the case for many herbicides, true resistance would be even rarer at the time the proactive monitoring was initiated.

4. Monitoring herbicide performance inquiries for possible cases of resistant weeds can be a means to facilitate the detection of resistance in an area, raising awareness and potentially spurring greater adoption of BMPs. However, visual determination of resistance in the field is subjective, prone to confusion with other factors affecting performance, and should be confirmed through laboratory or greenhouse testing.

   Farmers often report instances of poor herbicide performance to their local retailer, and in many cases, these product complaints are passed on to the manufacturer for resolution. Monitoring performance inquiries has been the primary means by which resistance in a new species or in a new geography has been identified. This method also provides qualitative assessment of the intensity and distribution of resistance within an area. During recent product registrations in the United States, this system was identified as a means of detecting resistant weeds during the early stages of infestation.

   Investigation of performance inquiries is a workable method to identify resistance, but there are challenges to using this method as an avenue for "early" detection of resistant weeds. These include (1) the time elapsed between initial development of resistance and the point at which the issue becomes noticeable, (2) the subjectivity of visual determinations of resistance, and (3) the time required for confirmation of resistance and communication to others. Based on past experience, most farmers do not recognize or acknowledge a decline in overall product performance until the extent of resistance becomes significant, which, in most cases, is defined as failure to control 10 to 20% of the population. This is generally 2 or more yr after resistance has become established in a field. In addition, a visual determination of resistance can often be confused with other factors affecting herbicide performance, such as weather or application issues. It can take at least 6 to 12 mo to harvest seed from the suspect population and conduct the controlled-environment testing necessary for confirmation of suspected resistance. For some weed species, this means resistance will have spread to other fields by the time it is confirmed in the source field. Overall, early identification is still a worthy goal and could facilitate managing and slowing the spread of a resistant weed. Better training on how to recognize resistance in the field, along with more rapid methods of confirmation, could help achieve this goal.

5. Resistance monitoring processes for weeds are fundamentally different from those for insects or diseases. Methods such as baseline monitoring that are used for these other pests are not readily transferable to weeds.

Although monitoring programs for insecticide and fungicide resistance may offer some concepts that can be applied to herbicide resistance, basic biological differences among the taxa will drive very different approaches. The primary biological factors contributing to these differences are their mobility (insects), inheritance of resistance genes (dominant or recessive), and the time interval between generations for both insects and fungi (multiple generations over a short period). Monitoring for insecticide resistance is primarily accomplished by collecting targeted insects in strategically located field traps or by rearing insect populations in the laboratory (IRAC 2013). Because many insects are mobile, resistance monitoring traps in a fairly large area covering many fields can be installed for a reasonable cost and minimal resources. Monitoring for fungicide resistance has some similarity to that of HR, where individual fields are sampled, and collections are evaluated using bioassays. However, they differ in the ease of implementing their sampling and the individual bioassay methods, and thus, the resources and time required to complete testing, with fungi resistance testing generally being the easier to complete (Brent and Hollomon 2007).

Mitigation

Once resistance is detected, steps may be taken to mitigate its impact. In the context of herbicide resistance, we define *mitigation* as the action of reducing the spread, severity, and economic impact of resistance, in contrast with *remediation*, which is sometimes equated with *eradication* of resistant individuals. A critical aspect of mitigation is the implementation of BMPs, which is facilitated by effective education and training programs (Norsworthy et al. 2012). Education around BMPs can be enhanced by using information from monitoring studies and early detection of resistant populations. In addition, education can improve the adoption and likely success of mitigation efforts. For mitigation, HRAC believes the following points should be considered:

1. Better procedures need to be developed to facilitate earlier communication between herbicide providers, academics, consultants, and farmers regarding cases of resistance. The procedures must emphasize the need for accuracy and consider privacy and confidentiality issues of farmers, academics, and companies.

   Faster communication of confirmed resistance to farmers will facilitate more-timely decisions about changing practices and reinforce the need for preventative BMPs. More-timely communication of confirmed resistance, and even for those situations under investigation for resistance (i.e., cases defined as *likely resistant*), across the technical community would allow experts in other areas to be vigilant about impending resistance and to actively consider ways to mitigate a particular type of resistance. Closing the communication gap between researcher and farmer and within the research/technical community is an effort that needs attention and for which, better procedures need to be developed. However, the need to increase speed of communication must be tempered with the need to be as accurate as possible in what is being communicated. There are also privacy and confidentiality issues for farmers, academics, and companies that need to be addressed as new procedures are evaluated.
2. The primary goal of mitigation programs is to contain or slow the spread of resistant populations. Only in rare cases, can eradication be a goal. Effective mitigation is accomplished through enhanced farmer awareness and implementation of resistance BMPs, as well as coordinated efforts of technical experts

   Given weed seedbank dynamics and seed dormancy, most weed scientists would agree that eradication is typically not feasible. The implementation of an effective mitigation program is dependent on the early identification of resistance and the availability of cost effective tools to manage, contain, or, in rare cases, eliminate the resistant population before it spreads. This is also influenced by (1) the number of trained individuals monitoring for resistance, (2) the biological characteristics (reproduction, longevity of seed, among others) of the weed species, (3) early identification of a population that includes truly resistant individuals, and (4) farmer involvement in early identification and in mitigation efforts. Some species will be essentially impossible to contain because of their reproductive and seed-dormancy characteristics. Little has been published on mitigation but, in some cases, manufacturers and public institutions have undertaken efforts to contain instances of new resistant weeds, with mixed results. Nevertheless, the effort may be worthwhile if the biological characteristics of the weed are favorable and the consequences of not containing the resistance are substantial.

Ultimately, no single monitoring method can provide a complete and accurate determination of the extent of herbicide resistance. The different methods described above can help provide insights into different facets of the problem, but a full understanding is gained only through a combination of information sources. Monitoring for resistance can increase awareness, improve adoption of BMPs, and, coupled with mitigation programs where appropriate, ultimately help preserve our valuable herbicide resources. The goal of both monitoring and mitigation is to limit the negative economic and environmental impacts of resistance. All parties involved in weed management have responsibility for the early detection, monitoring, and mitigation of HR. Individual active-ingredient registrants should be primarily responsible for the collection, handling, and timely communication of performance failures under investigation and those confirmed as being due to resistance. Monitoring programs that define the scope and spread of resistance should continue to be proposed and implemented by either public or private weed scientists, on a case by case basis, and resourced through public and private funding. Mitigation programs with realistic goals should be the joint responsibility of the primary registrant of an active ingredient and local weed-management experts. Collaboration among these stakeholders can be fostered through professional weed-science organizations (e.g., WSSA), with the overall goal of sustainable weed management. In closing, the reader is invited to scrutinize a more in-depth discussion of these points, which is found on the HRAC Web site: (http://www.hracglobal.com/pdfs/monitoring%20and%20mitigation.pdf).

Literature Cited

Amason R (2013) Data on Glyphosate Resistant Kochia Surprises Experts. The Western Producer. http://www.producer.com/2013/05/data-on-glyphosate-resistant-kochia-surprises-experts/. Accessed May 7, 2015

Baumgartner JR, Al-Khatib K, Currie RS (1999) Survey of common sunflower (*Helianthus annuus*) resistance to imazethapyr and chlorimuron in northeast Kansas. Weed Technol 13:510–514

Beckie HJ, Heap IM, Smeda RJ, Hall LM (2000) Screening for herbicide resistance in weeds. Weed Technol 14:428–445

Beckie HJ, Lozinski C, Shirriff S, Brenzil CA (2013) Herbicide-resistant weeds in the Canadian Prairies: 2007 to 2011. Weed Technol 27:171–183

Bourgeois L, Morrison IN, Kelner D (1997) Field and producer survey of ACCase resistant wild oat in Manitoba. Can J Plant Sci 77:709–715

Brent KJ, Hollomon DW (2007) Fungicide Resistance in Crop Pathogens: How Can it be Managed? Fungicide Resistance Action Committee Monograph No. 1. http://www.frac.info/docs/default-source/publications/monographs/monograph-1.pdf?sfvrsn=8. Accessed June 1, 2015

Davis VM, Gibson KD, Johnson WG (2008) A field survey to determine distribution and frequency of glyphosate-resistant horseweed (*Conyza canadensis*) in Indiana. Weed Technol 22:331–338

Duke SO, Powles SB (2009) Glyphosate-resistant crops and weeds: now and in the future. Agbioforum 12:346–357

Falk JS, Shoup DE, Al-Khatib K, Peterson DE (2005) Survey of common waterhemp (*Amaranthus rudis*) response to protox- and ALS-inhibiting herbicides in northeast Kansas. Weed Technol 19:838–846

Foresman C, Glasgow L (2008) US grower perceptions and experiences with glyphosate-resistant weeds. Pest Manag Sci 64:388–391

Givens WA, Shaw DR, Newman ME, Weller SC, Young BG, Wilson RG, Owen MD, Jordan DL (2011) Benchmark study on glyphosate-resistant cropping systems in the United States, part 3: grower awareness, information sources, experiences and management practices regarding glyphosate-resistant weeds. Pest Manag Sci 67:758–770

Hanson BD, Shrestha A, Shaner DL (2009) Distribution of glyphosate-resistant horseweed (*Conyza canadensis*) and relationship to cropping systems in the Central Valley of California. Weed Sci 57:48–53

[IRAC] Insecticide Resistance Action Committee (2013) Industry Perspectives on Insect Resistance Monitoring for Transgenic Insect-Protected Crops. http://www.iraconline.org/documents/industry-perspectives-on-ir-monitoring/?ext=pdf. Accessed January 5, 2015

Jander G, Baerson SR, Hudak JA, Gonzalez KA, Gruys KJ, Last RL (2003) Ethylmethanesulfonate saturation mutagenesis in *Arabidopsis* to determine frequency of herbicide resistance. Plant Physiol 131:139–146

Légère A, Beckie HJ, Stevenson FC, Thomas AG (2000) Survey of management practices affecting the occurrence of wild oat (*Avena fatua*) resistance to acetyl-coA carboxylase inhibitors. Weed Technol 14:366–376

Neve P, Norsworthy JK, Smith KL, Zelaya IA (2011) Modelling evolution and management of glyphosate resistance in *Amaranthus palmeri*. Weed Res 51:99–112

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60:31–62

Owen M, Walsh M, Llewellyn R, Powles S (2007) Widespread occurrence of multiple herbicide resistance in annual ryegrass (*Lolium rigidum*) populations within the western Australian wheat belt. Aust J Agric Res 58:711–718

Powles SB, Preston C, Bryan IB, Jutsum AR (1996) Herbicide resistance: impact and management. Adv Agron 58:57–93

Zhou X, Larson JA, Lambert DM, Roberts RK, English BC (2015) Farmer experience with weed resistance to herbicides in cotton production. Agbioforum 18:114–125

Received June 29, 2015, and approved July 4, 2015.

Associate editor for this paper: William Vencill, University of Georgia.