Weeds 2011: What is new, herbicide-resistant weeds and management tactics

Micheal D. K. Owen
Iowa State University, mdowen@iastate.edu

Weeds 2011: What is new, herbicide-resistant weeds and management tactics

Micheal D.K. Owen, professor and extension weed specialist, Agronomy, Iowa State University.

Introduction

Weeds have a major impact on global agricultural profitability and represent the most important pest complex to the well-being of mankind. In 2004, the ubiquitous nature of weeds impacted U.S. agriculture representing a $20 billion cost to the growers (Basu et al., 2004; Bridges, 1994). Currently, herbicide-resistant weeds likely represent an even greater economic threat to U.S. agriculture. Herbicide resistance is not a concern specifically focused upon genetically-engineered crops however the incredible global change in the agricultural landscape attributable to this technology has significantly impacted the evolution of herbicide-resistant weeds. Currently, there are over 340 herbicide-resistant weed biotypes in more than 190 different plant species (Figure 1) (Heap, 2010). Recently, herbicide-resistant weeds have gained much attention nationally, despite the fact that herbicide-resistant weeds have been an economic issue to agriculture for more than three decades. Consider that the report from the National Research Council which brought attention to herbicide-resistant weeds in glyphosate-resistant crops resulted in the House Oversight Committee on Domestic Policy convening a hearing to debate the implications of evolved weed resistance to glyphosate (http://oversight.house.gov/index.php?option=com_jcalpro&Itemid=1&extmode=view&extid=197) (Ervin et al., 2010) . Thus, it is clear that herbicide-resistant weeds will continue to have a major role in the future of Iowa agriculture. The issues reflect, in part, an inability or unwillingness on the part of growers and agricultural chemical and seed companies to fully embrace the problem and change weed management programs. This paper will address the current situation with regard to herbicide-resistant weeds, report on changes in the agricultural chemical industry and provide perspectives and suggestions to resolve weed management problems.

What is new for Iowa weed management?

The information included in this section reflects the update information received from the agricultural chemistry industry. Inclusion of update information does not constitute a recommendation nor does the lack of inclusion constitute a lack of support on the part of ISU Weed Science Extension.

BASF

BASF has expanded the Integrity herbicide label to include soybeans and changed the name to Verdict powered by Kixor herbicide. Verdict is a combination of saflufenacil and dimethenamid-P and should be applied prior to crop emergence. The saflufenacil component of Verdict is a PPO inhibitor herbicide and has excellent burndown activity on sensitive weeds. Saflufenacil has demonstrated inconsistent control of PPO resistant common waterhemp. If crops have emerged prior to Verdict application, do not apply as the likelihood of crop injury is high. In corn, Verdict can be applied preplant surface, preplant incorporated or preemergence. Field corn (grain and silage) and popcorn are described on the Verdict label. In soybeans, Verdict may be applied in the fall or in the spring early preplant through preemergence. A minimum preplant interval of 30 days is required on coarse (sand, loamy sand and sandy loam) soils with < 2% organic matter. No preplant interval is required on coarse soils with > 2% organic matter and all medium and fine textured soils.

Bayer Crop Science

Bayer Crop Science has initiated an important effort to provide growers with a better understanding of the implications of evolved resistance to herbicides, particularly glyphosate. These efforts include, but are not limited to hosting an international conference (Pan-American Weed Resistance Conference) in January, 2010 and field meetings in the Mississippi Delta regions in the summer and fall, 2010. They are promoting stewardship for weed management in order to minimize the evolution of glyphosate-resistant weeds. Interestingly, the first weed with resistance to glufosinate (Ignite) was recently reported (http://paraquat.com/news-and-features/archives/first-case-of-glufosinate-resistance-recorded).

Capreno will be widely available in 2011. The herbicide premixture contains an ALS inhibiting herbicide (thiencarbazone-methyl), an HPPD inhibiting herbicide (tembotrione) and a safener (isoxadifen). Other products such as Balance Pro and Option will not be available in 2011. Balance Pro has been replaced with Balance Flexx which includes isoxaflutole and a safener (cyprosulfamide) thus allowing early postemergence application through V2 stage of corn development. However, ISU recommends that Balance Flexx is best used as an early preplant or preemergence application.

Bayer Crop Science is also developing HPPD-resistant genetically-engineered crops. Given the current political situation and the impact it may have on registration of new technologies, it is unclear what the results of the research will be.

Dow AgroSciences

Dow AgroSciences has launched an aggressive stewardship campaign describing the evolution of glyphosate-resistant weeds, the perspectives offered by growers and the benefits growers describe for glyphosate and genetically-engineered crops. These efforts included surveys and informational reports in the popular agricultural press. Not surprisingly, the most important benefit for the glyphosate-based crop systems described by growers from the surveys was the simplicity for managing weeds provided by the glyphosate-based systems. Also concerning was the report from a survey conducted in June 2010 that only 38% of growers reported that glyphosate-resistant weeds were a significant or very significant threat. These informational reports provided insights about why glyphosate-resistant weeds are important considerations and why growers should provide stewardship to preserve the viability of the glyphosate-based crop systems. Interestingly, 79% of the growers surveyed suggested that glyphosate-based crop systems would not be effective in ten or fewer years. The bottom-line message was that growers need to act now in order to protect the technology.

DuPont/Pioneer

DuPont has made a number of changes to the Resolve Q label. Resolve Q Is a mixture of rimsulfuron and thifensulfuron-methyl, both of which are ALS inhibiting herbicides. The changes include increasing the amount of rimsulfuron that can be used in a growing season from 0.5 to 1.0 oz A.I. per acre and the use of Resolve Q as a burndown trea*tm*ent for weeds. The latter is the same as described on the Basis (rimsulfuron) label. The Resolve Q label now describes the use of Prequel (rimsulfuron and isoxaflutole) and Breakfree (acetochlor) as tank mixture companions. Lastly, the re-crop restrictions for Resolve Q now are the same as those described on the Basis label.

Realm Q is a DuPont premixture of rimsulfuron and mesotrione that is available for contact plus residual weed control with or without glyphosate in corn. Realm Q also includes isoxadifen, a safener which minimizes the potential for corn injury. Realm Q can be applied to corn after emergence but prior to corn exhibiting seven leaf collars or being 20 inches tall.

DuPont/Pioneer continues to develop Optimum GAT corn and soybeans. The development of Optimum GAT soybean continues on the same timeline as previously reported; availability is anticipated in 2013-2014 pending field testing and regulatory approvals. Optimum GAT corn hybrids are anticipated later in the decade.

FMC Corporation

FMC Corporation has introduced Authority XL herbicide for use in soybeans to control a number of difficult weeds such as common waterhemp, giant ragweed and horseweed (marestail). Authority XL herbicide is a 70 DF formulation prepackage mixture of sulfentrazone (sulf) (62.2%) and chlorimuron-ethyl (CE)(7.78%) which represents a ratio of 8:1 sulf:CE; the ratio is 5:1 in Authority BL and Canopy XL. Authority XL herbicide provides two mechanisms of herbicide action; PPO inhibition and ALS inhibition. These product may not provide effective control of weeds that have multiple resistances to PPO and ALS inhibiting herbicides such as common waterhemp biotypes. Results of the soil-applied PPO inhibitor herbicides controlling PPO-resistant common waterhemp have been inconsistent in some instances. However the higher rates of PPO inhibitor herbicides used with preemergence applications may result in acceptable control of some common waterhemp biotypes that have been shown resistance to postemergence rates of PPO inhibitor herbicides.

Monsanto

Monsanto Company has a number of "new" products including TripleFLEX and Warrant herbicides. TripleFLEX is a prepackage mixture of acetochlor, flumetsulam and clopyralid and also contains dichlormid, a safener. TripleFLEX will be positioned for use on herbicide-tolerant corn (field and silage) including cultivars resistant to glyphosate and/or glufosinate. The three different herbicide mechanisms of action will provide a broad spectrum of weed control including some herbicide-resistant weed biotypes. Warrant is an encapsulated formulation of acetochlor that is specifically labeled for postemergence application in soybeans but timed to be preemergence to weeds. Encapsulation provides a safer formulation for the postemergence application timing. Application should be made before soybeans are R2. Optimum application timing, according to the Warrant label, is V2-V3. A second directed application can be made at V5-V6 stage of soybean development. The emphasis for Warrant will be the residual control of difficult small-seeded broadleaf weeds (i.e. common waterhemp) and annual grasses. Warrant does not provide control of emerged weeds.

Monsanto has also established partnerships with several companies in order to better manage glyphosate-resistant weed biotypes and provide stewardship for the Roundup Ready technologies. Specifically, Monsanto has agreements with Sumitomo Chemical Company, Ltd. and Valent U.S.A. Corporation for the use of flumioxazin (Valor) including Valor SX (flumioxazin), Valor XLT (flumioxazin and chlorimuron-ethyl) and Gangster multipack (flumioxazin and cloransulam-methyl). The arrangement also includes Select (clethodim).

Monsanto has also has an agreement with FMC Corporation for products including Authority First DF (sulfentrazone and cloransulam-methyl), Authority MTZ (sulfentrazone and metribuzin), Authority XL (sulfentrazone and chlorimuron-ethyl) and Authority Assist (sulfentrazone and imazethapyr).

Monsanto continues to develop the dicamba-resistant genetically-engineered soybean cultivars. However, this technology was the focus of the recent discussion at the House Oversight Committee Hearings on Domestic Policy. The discussions were not positive and there were mixed perspectives about the benefits and risks of the technology from a number of witnesses who testified at the hearings.

Syngenta

Syngenta has reported a number of "new" products including Callisto Xtra (mesotrione and atrazine), Flexstar GT (fomesafen and glyphosate) and Peak (prosulfuron). Callisto Xtra is labeled for postemergence application in field corn, seed corn, sweet corn, silage corn and yellow popcorn. Flexstar GT is specifically registered for glyphosate-resistant soybean and has provided control of some glyphosate-resistant weed biotypes. Peak is now registered for weed management in corn. There are a number of restrictions and precautions on the supplemental label that describes corn including concerns for applications to stressed corn, interactions with organophosphate insecticides and potential interactions with other herbicides. Peak has demonstrated good activity on burcucumber.

There are also a number of label updates for Fusilade DX (fluazifop-P-butyl), Flexstar (fomesafen), and Prefix (S-metolachlor and fomesafen). Fusilade DX can now be applied post-bloom to soybeans and has a 60 day post harvest interval. Flexstar has numerous updates described on the label such as changes for application timing, adjuvants and rain-fastness. Prefix has several additions to the label including the application of Ignite following Prefix applications the removal of restrictions of S-metolachlor prior to postemergence application of Prefix . Bicep II MAGNUM (S-metolachlor and atrazine) can now be applied postemergence to corn 5-12 inches tall. Callisto, Callisto Xtra, and Halex GT labels now include language about HPPD-resistant weeds.

Valent U.S.A. Corporation

Valent U.S.A. Corporation has a registration pending for Fierce herbicide. Fierce is a prepackage mixture of flumioxazin and pyrosulfone and will be registered as a preemergence herbicide in soybean, no-tillage and reduced tillage corn production and as a fall burndown treatment. Pyroxasulfone has been studied for a number of years as the Kumiai Chemical Industry Co., LTD product KIH-485 and has a described mechanism of action as a shoot growth inhibitor and attacks the enzyme responsible for long chain fatty acid elongation. Flumioxazin is a PPO inhibitor herbicide. Fierce has demonstrated good control of many annual grasses and small-seeded annual broadleaf weeds and has good residual properties.

Concept of "superweeds" – ecologically true or a popular press attempt to garner attention?

The concept of "superweed" has gained considerable traction in the popular press and in political arenas but is very misleading and ecologically inaccurate. The term "superweed" should be ecologically based on the presumption that herbicide resistance, specifically resistance to glyphosate in weeds, improves the fitness of the resistant weed biotype. However, this is not the case; glyphosate-resistant weeds are no more ecologically fit than susceptible populations. Furthermore, an assessment of the fitness of herbicide-resistant weed biotypes is critical when determining the ability of the biotype to adapt and impact agriculture, thus possibly achieving "superweed" status. To that end, the evolution of herbicide resistance has not typically enhanced the fitness of the herbicide-resistant weed biotypes compared to sensitive weed biotypes and in some cases has reduced the fitness of the resistant weed populations (Gressel, 2002). Thus, there is no pervasive evidence that herbicide-resistant weed populations behave differently than herbicide-sensitive weed populations in the absence of the herbicide, thus suggesting that herbicide resistance confers "superweed" status on glyphosate-resistant weed populations is a considerable overstatement of the reality. However, it does gain considerable public and political attention and sells magazines.

Management of weeds: the implications of herbicide use and other tactics

The recurrent use of any herbicide or herbicide mechanism of action imparts selection pressures on a weed population and thus creates an ecological advantage to those rare individual weeds within the population that have a heritable mutation conferring the ability for these weeds to survive the herbicide, particularly if no other alternative management tactics are included (Llewellyn et al., 2001; Owen and Zelaya, 2005). Similarly, the recurrent use of any weed management tactic or crop production strategy will also select for weed biotypes or species that are ecologically adapted ("fit") and thus provide them with an ecological opportunity to become dominant within the weed community (Owen, 2008b).

The most important agricultural manipulation, or selective forces, that affect changes in weeds are tillage (disturbance) and herbicide use which will cause the composition of the weed communities to change to species that no longer are affected by these practices (Owen, 2008b). Herbicides tend to impart greater and more consistent selective force on a weed community resulting in relatively faster changes or shifts in species composition than tillage, although both are ultimately important (Heard et al., 2003; Heard, 2003).

The current weed management strategies reflect the wide-spread utilization of the glyphosate-resistant crop cultivars and the use, often exclusively, of glyphosate. Specifically, the lack of diversity in weed management is largely attributable to grower management decisions without due consideration to the inevitable consequences of the impact on weed communities. There has generally been a lack of integrated weed management (IWM) practices employed by growers (Swanton and Weise, 1991). The primary benefits of the genetically-engineered crops, as stated by growers, is the convenience and simplicity of weed control (Bonny, 2007; Owen, 2008a). This has contributed to the dramatic decline in alternative tactics used to manage weeds and thus loss of IWM in the in Iowa and the United States. The loss of IWM results in weed shifts in the genetically-engineered crops which negatively impacts crop production economics and has important long-term implications on the sustainability of genetically-engineered crop systems (Owen and Boerboom, 2004; Owen, 2008b; Sammons et al., 2007).

While the lack of diversity for weed management tactics and subsequent changes in weed communities may not eliminate the use of glyphosate, it does provide a strong impetus for the development of improved weed management strategies and the adoption of more diverse IWM tactics (Table 1) (Green, 2007; Swanton and Weise, 1991).

Current state of herbicide-resistant weeds

The current status of herbicide-resistant weeds from a global perspective strongly supports the premise that new herbicide-resistant weed populations continue to evolve at an increasing rate. Weeds have evolved resistance to 20 different herbicide mechanisms of action (Heap, 2010). Most recently, HPPD inhibitor herbicide-resistant common waterhemp (*Amaranthus tuberculatus* syn. rudis) was reported in Iowa and Illinois. Currently there are 20 weeds confirmed to have evolved resistance to glyphosate and 11 in the U.S. (Table 2 and Figure 2) (Heap, 2010). Iowa has glyphosate-resistant populations of giant ragweed (*Ambrosia trifida*), horseweed (*Conyza canadensis*) and common waterhemp distributed widely across the state.

Management of weeds resistant to glyphosate and other herbicides

As a result of ill-advised use of herbicides, weeds have inevitably evolved genetically-heritable resistance to herbicides (Owen, 1997). This exhibition of "Darwinian evolution in fast forward" is a consequence of the effectiveness and consistency of herbicides in managing weed complexes. Also, other weeds with natural tolerance are becoming more economically important in crop systems based on genetically-engineered cultivars (Culpepper, 2006). Thus concern for and management of weeds that no longer respond to glyphosate has taken on a particularly important perspective in Iowa agriculture. It is unfortunate that surveys, while somewhat dated, indicated that generally growers are not overly concerned about glyphosate-resistant weeds (Johnson et al., 2009).

The management of glyphosate- and herbicide-resistant weeds must include as many tactics as possible (Table 1). Given the current crop production systems, these solutions will focus on herbicides almost to the exclusion of other tactics. Importantly, there are short-term gains than can be realized with tactics such as herbicide rotation, herbicide tank mixtures and other genetically-engineered traits (i.e. glufosinate). Importantly, growers must recognize that tactics they can and will adopt to mitigate glyphosate-resistant weed problems have different "returns"; herbicide rotation tends to provide only one year of benefit for each year of adoption while the use of herbicide mixtures is a much more effective strategy (Beckie, 2006; Maxwell and Jasieniuk, 2000).

Studies conducted in grower fields in Iowa during 2009 and 2010 (data from 2010 reported) demonstrated conclusively that herbicide-resistant weeds can be effectively managed with the correct selection of herbicides. These studies validated the existence of glyphosate-resistant populations of giant ragweed and common waterhemp as well as populations of common waterhemp with resistance to PPO inhibitor herbicides. These herbicide-resistant weed populations were managed with the alternative herbicides included in the experiments (Tables 3-5). Interestingly, these experiments also confirmed the existence of multiple resistances in these weed populations; at each location, the weed population was not only resistant to the target herbicide but also resistant to imazethapyr (PursuitTM). Research conducted in grower fields has confirmed that common waterhemp populations in Iowa are resistant to ALS inhibitor herbicides and demonstrated the existence of cross resistance to ALS inhibitor herbicides in common waterhemp populations (Hinz and Owen, 1997). Suggestions of herbicides alternatives to glyphosate or to be used in combination with glyphosate (in sequence or as a tank mixture) and the relative efficacies on giant ragweed, common waterhemp and common lambsquarters are reported in Tables 6 and 7.

Conclusions

Weeds represent the most economically important pest complex to global food production and also significantly impact mankind at all levels, from health perspectives to the pursuit of recreation (Bridges, 1994). Interestingly, the better weed management becomes, the more difficult it becomes to manage weeds. This conundrum reflects the diversity of weed genomes facilitating their continued adaptation to all forms of selective practices (control) necessary for effective crop production (Barrett, 1983; De Wett and Harlan, 1975; Gould, 1991). During the last five decades, herbicides have been an important component for effectively managing weeds. As a result, biochemical adaptation or "mimicry" has become an important problem (Gould, 1991). Recent efforts to manage weeds have taken a slightly different path and focus on the use of herbicides that are selective to crops due to genetic-engineering (Duke and Powles, 2008). Glyphosate in genetically-engineered crops has provided exceptional control of many weeds. Thus, weed management has been deemed simple and convenient with the use of genetically-engineered crops despite the inevitability that weed populations would again rise to the genetic challenge and resistance to glyphosate would evolved despite suggestions otherwise (Bradshaw et al., 1997; Neve, 2007). Furthermore, short-sighted recommendations from the industry contributed to the problems (Sammons et al., 2007).

The ability to effectively manage herbicide-resistant weeds including those resistant to glyphosate is well-studied and tactics readily available to growers (Beckie, 2006). Models clearly demonstrate that the adoption of a diverse management approach to controlling weeds can prolong the utility of the genetically-engineered cultivars and glyphosate (Werth et al., 2008). Proactive management of glyphosate-resistant weeds is economically sustaining and provides stewardship for the genetically-engineered traits (Mueller et al., 2005). It is imperative that Iowa agricultural practices change immediately in order to maintain the viability of genetically-engineered crops and glyphosate and to improve economic returns on crop production.

References

Barrett, S. C. H. 1983. Crop mimicry in weeds. Economic Botany 37: 255-282.

Basu, C., Halfhill, M. D., Mueller, T. C., and Stewart Jr., C. N. 2004. Weed genomics: new tools to understand weed biology. Trends in Plant Science 9: 391-398.

Beckie, H. J. 2006. Herbicide-resistant weeds: management tactics and practices. Weed Technology 20: 793-814.

Bonny, S. 2007. Genetically modified glyposate-tolerant soybean in the USA: adoption factors, impacts and prospects. A review. Agronomy for Sustainable Development 28: 21-32.

Bradshaw, L. D., Padgette, S. R., Kimball, S. L., and Wells, B. H. 1997. Perspectives on glyphosate resistance. Weed Technology 11: 189-198.

Bridges, D. C. 1994. Impact of weeds on human endeavors. Weed Technology 8: 392-395.

Culpepper, A. S. 2006. Glyphosate-induced weed shifts. Weed Technology 20: 277-281.

De Wett, J. M. J., and Harlan, J. R. 1975. Weeds and domesticates: evolution in the man-made habitat. Economic Botany 29: 99-107.

Duke, S. O., and Powles, S. B. 2008. Glyphosate: a once-in-a-century herbicide. Pest Management Science 64: 319-325.

Ervin, D. E., Carriere, Y., Cox, W. J., Fernandez-Cornejo, J., Jussaume Jr., R. A., Marra, M. C., Owen, M. D. K., Raven, P. H., Wolfenbarger, L. L., and Zilberman, D. 2010. The impact of genetically engineered crops on farm sustainability in the United States. Washington, D.C.: National Research Council. 250 p.

Gould, F. 1991. The evolutionary potential of crop pests. American Scientist 79: 496-507.

Green, J. M. 2007. Review of glyphosate and ALS-inhibiting herbicide crop resistance and resistant weed management. Weed Technology 21: 547-558.

Green, J. M., and Owen, M. D. K. 2010. Herbicide-resistant crops: Utilities and limitations for herbicide-resistant weed management. Journal of Agricultural and Food Chemistry.

Gressel, J. 2002. Molecular biology of weed controlLondon: Taylor and Francis. Pp. 504.

Heap, I. 2010. The international survey of herbicide resistant weeds. Available at www.weedscience.com. Accessed 12 September 2010.

Heard, M. S., Hawes, C., Champion, G. T., Clark, S. J., Firbank, L. G., Haughton, A. J., Parish, A. M., Perry, J. N., Rothery, P., Scott, R. J., Skellern, M. P., Squire, G. R., and Hill, M. O. 2003. Weeds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. I. Effects on abundance and diversity. Philosophical Transactions of the Royal Society of London B 358: 1819-1832.

Heard, M. S., Hawes, C., G. T. Champion, S. J. Clark, L. G. Firbank, A. J. Haughton, A. M. Parish, J. N. Perry, P. Rothery, D. B. Roy, R. J. Scott, M. P. Skellern, G. R. Squire, and M. O. Hill. 2003. Weeds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. II Effects on individual species. Philosophical Transactions of the Royal Society of London B 358: 1833-1846.

Hinz, J. J. R., and Owen, M. D. K. 1997. Acetolactate synthase resistance in a common waterhemp (*Amaranthus rudis*) population. Weed Technology 11: 13-18.

Johnson, W. G., Owen, M. D. K., Kruger, G. R., Young, B. G., Shaw, D. R., G., W. R., Wilcut, J. W., Jordan, D. L., and Weller, S. C. 2009. U.S. farmer awareness of glyphosate-resistant weeds and resistance management strategies. Weed Technology 23: 308-312.

Llewellyn, R., Lindner, R. K., Pannell, D. J., and Powles, S. 2001. Adoption of integrated weed management to conserve the herbicide resource: review and framework. Available at http://www.agribusiness.asn.au/review/2001v9/Llewellyn_2001_1/Llewellyn.htm. Accessed 2/24, 2004.

Maxwell, B., and Jasieniuk, M. The evolution of herbicide resistance evolution models. Pages 172 in Proceedings of the Third International Weed Science Congress. Foz do iguassu

Mueller, T. C., Mitchell, P. D., Young, B. G., and Culpepper, A. S. 2005. Proactive versus reactive management of glyphosate-resistant or -tolerant weeds. Weed Technology 19: 924-933.

Neve, P. 2007. Challenges for herbicide resistance evolution and management: 50 years after Harper. Weed Research 47: 365-369.

Owen, M. 2008. Glyphosate resistant crops and evolved glyphosate resistant weeds - the need for stewardship. Pages 51 in Proceedings of the 5th International Weed Science Congress. Vancouver, Canada: IWSS.

Owen, M., and Boerboom, C. 2004. National Glyphosate Stewardship Forum. St. Louis, MO. 80 p.

Owen, M. D. K. 1997. Risks and benefits of weed management technologies. Pages 291-297 in R. De Prado, J. Jorrin, and L. Garcia-Torres, ed. Weed and crop resistance to herbicides. London: Kluwer Academic Publishers.

Owen, M. D. K. 2001. World maize/soybean and herbicide resistance. Pages 101-163 in S. B. Powles, and D. L. Shaner, eds. Herbicide resistance and world grains. Boca Raton: CRC Press.

Owen, M. D. K. 2008b. Weed species shifts in glyphosate-resistant crops. Pest Management Science 64: 377-387.

Owen, M. D. K., and Zelaya, I. A. 2005. Herbicide-resistant crops and weed resistance to herbicides. Pest Management Science 61: 301-311.

Sammons, R. D., Heering, D. C., Dinicola, N., Glick, H., and Elmore, G. A. 2007. Sustainability and stewardship of glyphosate and glyphosate-resistant crops. Weed Technology 21: 347-354.

Swanton, C. J., and Weise, S. F. 1991. Integrated weed managment: the rationale and approach. Weed Technology 5: 648-656.

Werth, J. A., Preston, C., Taylor, I. N., Charles, G. W., Roberts, G. N., and Baker, J. 2008. Managing the risk of glyphosate resistance in Australian glyphosate-resistant cotton production systems. Pest Management Science 64: 417-421.

Table 1. Assessment of cultural, mechanical and herbicidal tactics used for an Integrated Weed Management (IWM) program. Adapted from Green and Owen (2010) and Owen (2001) (Green and Owen, 2010; Owen, 2001)

Tactics	Benefits	Risks	Potential adoption and impact
Herbicide MOA rotation	Reduced selection pressure, possible control of HR weeds	Lack of available different MOAs, phytotoxicity, cost, weed spectrum not controlled by available alternatives	Excellent
Herbicide tank mixes	Reduced selection pressure, improved control on a broader weed spectrum	Poor activity on HR weed species, increased cost; potential phytotoxicity	Excellent
Variable herbicide application timing	Better control of HR species, more efficient use of herbicide(s)	Lack of herbicide residual activity, postemergence applications may be too late to protect yield potential, more application trips	Good to excellent
Adjusted herbicide rates	Better control of target species	Increased selection pressure (higher rates), selection for non-target site, polygenic resistance (lower rates)	Poor to fair
Herbicide banding	Reduced cost, reduced selection pressure, less herbicide used	Need for mechanical inter-row control tactics, specialized equipment, increased application time required	Poor
Precision herbicide application	Decreased herbicide use, reduced selection pressure	Increased cost of application, unavailability of consistent weed population maps; poor understanding of weed seedbank dynamics; increased variability of control	Poor
Herbicide synergists alternative products	Improved efficacy; reduced herbicide amount, possible new MOA	No research base; inconsistent efficacy, lack of available products	Poor
Herbicide resistant crops	No phytotoxicity, possible different MOA, possible reduced herbicide amount; application timing variable	Increased cost of traited seed; need for more applications per season; increased selection pressure from the MOA used, possible movement of HR trait into near-relative weeds, volunteer HR crops as weeds	Excellent
Primary tillage	Decreased selection pressure, excellent and consistent efficacy; depletion of weed seedbank	Increased time requirement, increases soil erosion, increased costs, requires additional tactics,	Good to excellent
Mechanical weed control strategies	Decreases selection pressure; consistent efficacy, relatively inexpensive	Increase time requirement, high level of management skill needed, requires additional tactics, potential for crop injury	Poor to fair
Crop rotation	Changes agro-ecosystem, allows different herbicide tactics (MOA, etc.), may facilitate other alternative strategies	Economic risk of alternative rotation crop, lack of adapted rotation crop, rotation crop not dissimilar and thus minimal impact on the weed community, requirement for herbicides	Fair to good
Adjusted time of planting	Potential improved efficacy on target weeds, reduction of selection pressure	Requires alternative strategies (primary tillage or herbicide application), potential for yield loss, need for increased rotation diversity	Poor to fair
Adjusted seeding rate	Reduced selection pressure, improved competitive ability for the crop	Increased seed cost, potentially increased pest problems, increased intraspecific competition, reduced potential yields	Fair
Alternative planting configuration	Improved competitive ability for the crop, reduced selection pressure	Unavailability of mechanical strategies, emphasis on herbicides, equipment limitations	Good
Selection of crop cultivars	Improved competitive ability for the crop, reduced selection pressure	Lack of research base, inconsistent impact on HR weed populations	Fair
Cover crops, mulches, intercrop systems	Improved competitive ability, reduced selection pressure, improved systems diversity, allelopathy	Inconsistent effect on HR weed populations, lack of understanding about the systems, limited research base, potential crop yield loss, need for herbicide to manage the cover crop, lack of good cover crop species	Poor
Seedbank management	Reduced HR weed pressure, reduced selection pressure	Lack of understanding about weed seedbank dynamics, requires aggressive tillage, emphasis on late herbicide applications, requires high level of management skills	Fair to good
Adjustment of nutrient use	Improved competitive ability for the crop, efficient use of nutrients, reduced selection pressure	Lack of research base, inconsistent results, potential for crop yield loss	Poor

Table 2. Weeds with evolved resistance to glyphosate in the United States of America[1]

Weed (common name)	State	Year of first report
Amaranthus palmeri (Palmer amaranth)	GA, NC, AR, TN, NM, AL, MS[2], MO	2005
Amaranthus tuberculatus (syn. rudis) (common waterhemp)	MO[2], IL[2], KS, MN, IA, MS	2005
Ambrosia artemisiifolia (common ragweed)	AR, MO, OH[2], KS	2004
Ambrosia trifida (giant ragweed)	OH[2], AR, IN, KS, MN, TN, IA, MO	2004
Conyza bonariensis (hairy fleabane)	CA[2]	2007
Conyza canadensis (horseweed)	DE, KY, TN, IN, MD, MO, NJ, OH[2], AR, MS, NC, PA, CA, IL, KS, MI, IA	2000
Kochia scoparia (kochia)	KS	2007
Lolium multiflorum (Italian ryegrass)	OR, MS, AR	2004
Lolium rigidum (rigid ryegrass)	CA	1998
Poa annua (annual bluegrass)	MO	2010
Sorghum halepense (johnsongrass)	AR, MS	2007

[1]Adapted from the International Survey of Herbicide Resistant Weeds (www.weedscience.org) (Heap, 2010)
[2]Biotypes demonstrating resistance to multiple herbicide mechanisms of action

Table 3. Control of glyphosate-resistant giant ragweed, 2010

Timing	Treatment	Rate	14 DAA	21 DAA	33 DAA
				% control	
*Pre	Saflufenacil	0.112 lbs ai/Ac	96	93	87
*Pre	Flumioxazin	0.095 lbs ai/Ac	0	0	0
*Pre	Sulfentrazone + Imazethapyr	0.28 lbs ai/Ac	23	23	23
*Pre	Flumioxazin + Pyroxasulfone	0.214 lbs ai/Ac	7	7	7
Post	Saflufenacil	0.0223 lbs ai/Ac	99	93	85
Post	Imazethapyr	0.0624 lbs ai/Ac	18	18	12
Post	Fomesafen + Glyphosate	1.86 lbs ai/Ac	98	96	95
Post	Lactofen	0.156 lbs ai/Ac	96	93	80
Post	Glyphosate	1.7 lbs ae/Ac	57	55	55
Post	Glyphosate	3.4 lbs ae/Ac	70	70	68
LSD (0.05)			6	8	10

*Ratings were taken 14, 21, and 33 days after post application and correspond to 38, 45, and 57 days after application (DAA) for pre treatments.

Table 4. Control of PPO-resistant common waterhemp, 2010

Timing	Treatment	Rate	15 DAA	22 DAA	29 DAA
				% control	
*Pre	Saflufenacil	0.112 lbs ai/Ac	88	91	91
*Pre	Flumioxazin	0.095 lbs ai/Ac	65	65	65
*Pre	Flumioxazin + Pyroxasulfone	0.214 lbs ai/Ac	77	77	77
*Pre	Sulfentrazone+ Imazethpyr	0.28 lbs ai/Ac	83	83	83
Post	Saflufenacil	0.0223 lbs ai/Ac	38	38	38
Post	Imazethapyr	0.0624 lbs ai/Ac	68	68	68
Post	Fomesafen + Glyphosate	1.86 lbs ai/Ac	99	99	99
Post	Lactofen	0.156 lbs ai/Ac	78	78	78
Post	Glyphosate	1.7 lbs ae/Ac	98	98	91
Post	Glyphosate	3.4 lbs ae/Ac	99	99	99
LSD (0.05)			31	31	32

*Ratings were taken 15, 22, and 29 days after post applications and correspond to 42, 49, and 58 days after application (DAA) for pre treatments.

Table 5. Control of glyphosate-resistant common waterhemp, 2010

Timing	Treatment	Rate	14 DAA	21 DAA	28 DAA
				% control	
*Pre	Saflufenacil	0.112 lbs ai/Ac	52	52	50
*Pre	Flumioxazin	0.095 lbs ai/Ac	92	92	87
*Pre	Sulfentrazone + Imazethapyr	0.28 lbs ai/Ac	96	95	92
*Pre	Flumioxazin + Pyroxasulfone	0.214 lbs ai/Ac	99	99	98
Post	Saflufenacil	0.0223 lbs ai/Ac	75	75	73
Post	Imazethapyr	0.0624 lbs ai/Ac	15	15	0
Post	Fomesafen + Glyphosate	1.86 lbs ai/Ac	91	91	88
Post	Lactofen	0.156 lbs ai/Ac	96	95	90
Post	Glyphosate	1.7 lbs ae/Ac	52	52	52
Post	Glyphosate	3.4 lbs ae/Ac	58	56	57
LSD (0.05)			10	10	8

*Ratings were taken 14, 21, and 31 days after post application and correspond to 58, 65, and 72 days after application (DAA) for pre treatments.

Table 6. Herbicides used in combination with glyphosate for control of giant ragweed, common lambsquarters and common waterhemp in corn (adapted from NDSU/UMN Extension publication). (P, F, G, E are poor, fair, good and excellent, respectively)

	Giant ragweed[1,2]	Common waterhemp[1,2,3]	Common lambsquarters
PRE in sequence with glyphosate			
Atrazine (0.5 to 1.0 lb ai/A)	F/G	G/E	G/E
Balance Flex	F	G/E	G
Banvel/Clarity	F	G	G
Callisto	F	G/E	E
Camix	G	G/E	E
Harness/Surpass/Dual/Outlook	P	G/E	F/G
Hornet	F/G	P/F	G
Integrity	G	G/E	G/E
Lumax	G	E	G/E
Prequel	F/G	E	G
Prowl	P	G	G/E
SureStart	F/G	G/E	E
POST as part of a tank mixture with glyphosate			
Aim	F	F/G	G
Atrazine (0.38 to 1.0 lb ai/A)	G	E	E
Banvel/Clarity	E	G	G/E
Basis	P	P	G/E
Buctril	G	G/E	G
Cadet	P	F	F
Callisto	G	E	G/E
Capreno	G	G/E	G/E
Hornet	G/E	P/F	P/F
Impact	G	G/E	G
Laudis	G	G/E	G/E
Option	P	P	P
Permit	P/F	P	P
Resolve Q	P	P	F
Resource	P	F	F
Status/Distinct	G/E	G/E	G/E
Alternative Technology			
Ignite in Liberty Link corn hybrids	G/E	G	F

[1]ALS inhibitor herbicide resistant biotypes have been confirmed in Iowa
[2]Glyphosate resistant biotypes have been confirmed in Iowa
[3]PPO inhibitor herbicide resistant biotypes have been confirmed in Iowa

Table 7. Herbicides used in combination with glyphosate for control of giant ragweed, common lambsquarters and common waterhemp in soybean (adapted from NDSU/UMN Extension publication). (P, F, G, E are poor, fair, good and excellent, respectively)

	Giant ragweed[1,2]	Common waterhemp[1,2,3]	Common lambsquarters
PRE in sequence with glyphosate			
IntRRo (alachlor)	P	F/G	P/F
Dual/Outlook	P	F/G	P/F
Authority Assist	P	G/E	E
Authority First/Sonic	G	G/E	G/E
Authority MTZ	P/F	G/E	G
Boundary	P/F	G/E	G
Enlite	F	FG/E	F
FirstRate	G/E	P	G
Gangster	F/G	G	G/E
Optill	F/G	G	G/E
Prefix	F	G	G
Prowl	P	G	G
Sencor	P	E	E
Sharpen (1 oz/A)	F	G	G/E
Spartan	F	E	G/E
Treflan	P	G	G
Valor	F	G/E	E
POST as part of a tank mixture with glyphosate			
Cadet	P	F	F
Classic	F	P	P
Cobra/Phoenix	F/G	E	F
FirstRate	E	P	P
Flexstar	G	E	F
Harmony GT	P	P	G/E
Pursuit	F	P	P/F
Raptor	G	P	G
Resource	P	G	F
Synchrony	F/G	P	G/E
Ultra Blazer	F	E	F
Alternative Technology			
Ignite in Liberty Link soybean hybrids	G/E	G	G

[1]ALS inhibitor herbicide resistant biotypes have been confirmed in Iowa
[2]Glyphosate resistant biotypes have been confirmed in Iowa
[3]PPO inhibitor herbicide resistant biotypes have been confirmed in Iowa

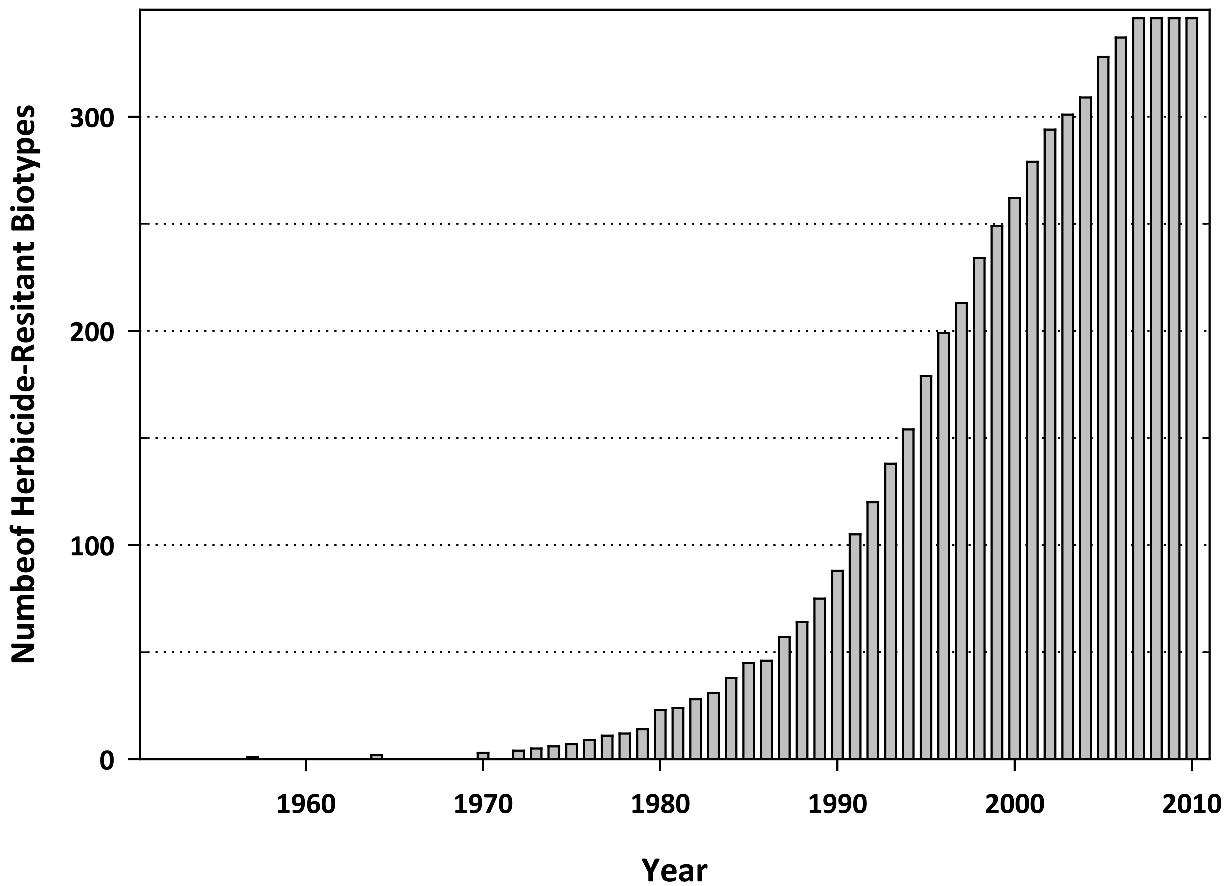

Figure 1. Cumulative global total of herbicide-resistant weed biotypes 1952-2010. Adapted from the International Survey of Herbicide Resistant Weeds (www.weedscience.org) (Heap, 2010)

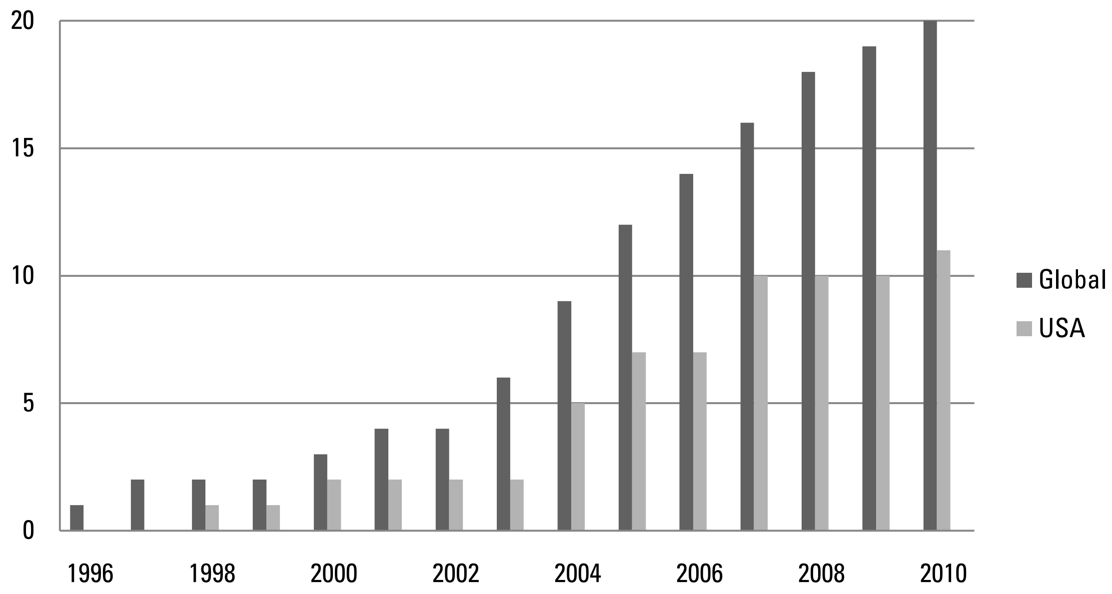

Figure 2. Occurrence of weeds with evolved resistance glyphosate. Adapted from the International Survey of Herbicide Resistant Weeds (www.weedscience.org) (Heap, 2010)