Herbicide Resistance Factsheet Series

How to Manage Herbicide Resistance with IWM

Integrated weed management (IWM) describes the practice of using multiple control tactics to manage weeds. This GROW educational page will dive deeper into **how integrated approaches using both chemical and non-chemical tactics can help prevent and manage herbicide-resistant weeds on your farm**. It presents a comprehensive overview of herbicide resistance management through a series of sections, which give the reader detailed answers to 10 fundamental questions. Let GROW be part of your solution to better weed management.

Section 1: What is Integrated Weed Management (IWM)?

Integrated weed management (IWM) is a system that layers multiple weed control methods to suppress and manage weeds over time, by targeting weeds in diverse ways and at various stages of development. IWM requires expanding your weed management practices over more than one season. This requires a better understanding of the weed species present in the field and their biology, such as lifecycle, emergence timing, growth rate, and seed production. The result is a robust weed management program that doesn't rely on a single herbicide mode of action or any other sole management tactic. In general, IWM techniques include Prevention, Cultural, Chemical, Mechanical, and Biological tactics (Figure 1). See more details on these GROW webpages on **what IWM is** and how you can **combine weed control tactics effectively**.

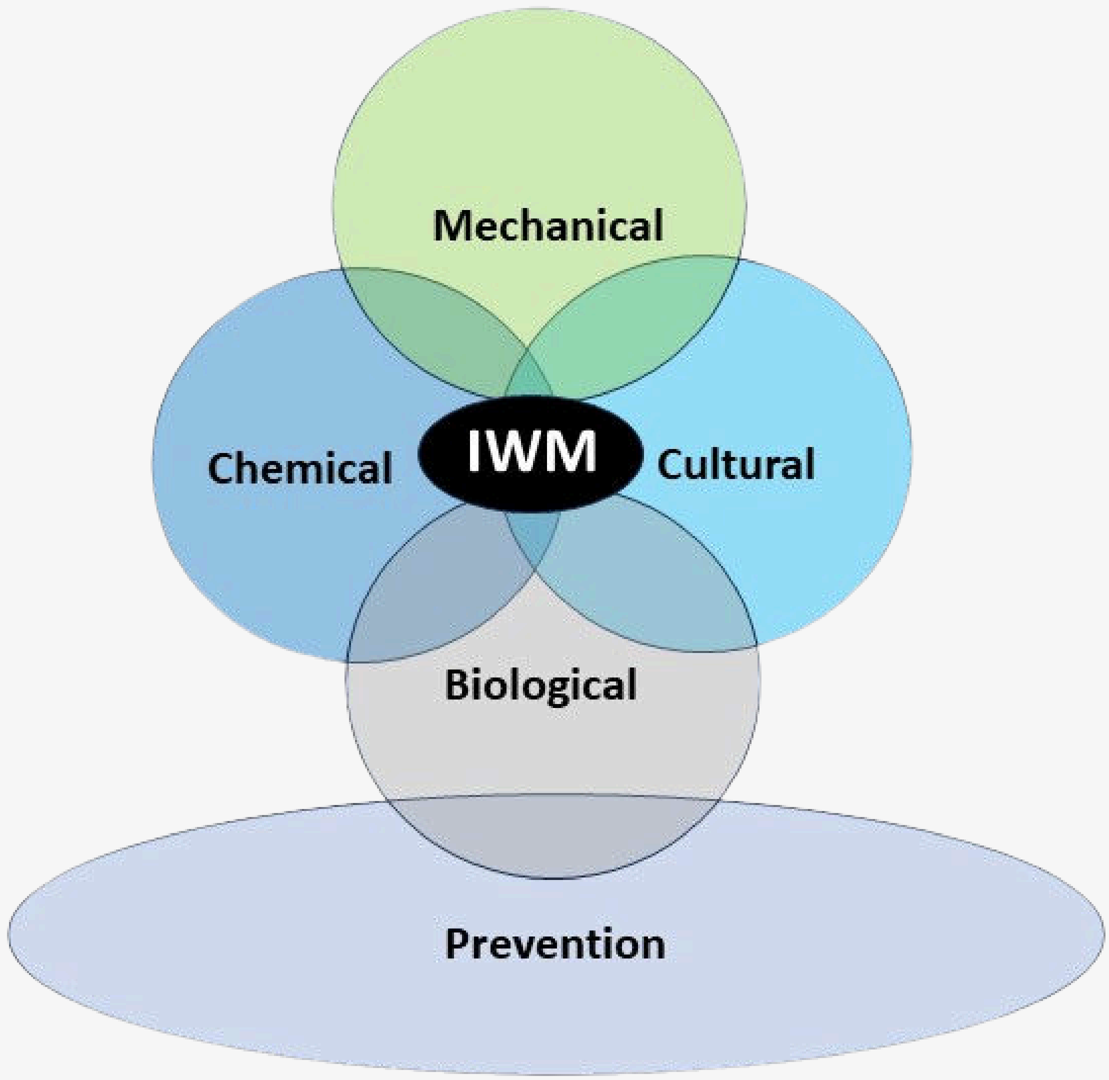


Figure 1. IWM is composed of prevention, cultural, chemical, mechanical, and biological tactics. (Graphic credit: A. Klodd)

Section 2. What strategies are important for implementing IWM?

A number of approaches should be used when managing herbicide resistance. Prevention and control are key and aim to head off the introduction of resistant weeds in a field or reduce an already established problem. Monitoring crop fields and weed populations by regularly scouting should be implemented to help guide decisions (Figure 2).

Preventative tactics for herbicide-resistant weeds should focus on avoiding weed seed introduction from contaminated crop seed, soil, manure, compost, hay, livestock feed, machinery, neighboring fields and field edges (Figure 3). In addition to seeds from annual and biennial species, the vegetative structures such as rhizomes, stolons, tubers, and bulbs of some perennials can also help spread problem weed infestations. In addition, prevention should go much further and include tactics that also slow the resistance evolution process by reducing weed exposure to herbicides within the same MOA group and integrating multiple management strategies that prevent selection and spread. See our webpage, growiwm.org/prevention/, for detailed information on prevention.

Figure 2. Scouting is a key step in the prevention of herbicide resistance.

Section 2 (cont.)

Manage vegetation along field edges, fence rows, and ditch banks such as in this soybean field in Delaware. (Photo credit: Claudio Rubione, GROW)

A mower deck contaminated with weed seeds. (Photo credit: Michael Flessner, VA Tech)

Straw, chaff, and potential weed seed being spread during combine harvest (Photo credit: Claudio Rubione, GROW)

Certain weed seeds can be difficult to separate from some crop seeds during the harvesting process. This image shows jointed goatgrass contaminated wheat. This can be a particular problem when seed is saved and replanted. Using certified weed-free crop seed or thoroughly cleaning saved seed can prevent this problem. (Photo credit: Phil Westra, Colorado State University, Bugwood.org)

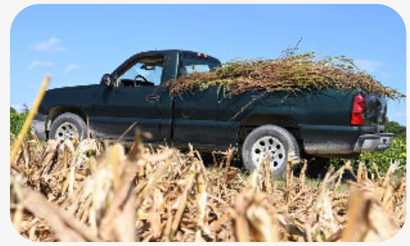
Figure 3. Weed seeds can spread across the farm many ways.

IWM is essential to help prevent yield and quality loss, halt the introduction of more weed seed, and reduce the problem over time. Cultural, chemical, mechanical, and sometimes biological weed control tactics are critical for maintaining successful and profitable crop production (Figure 4). If you discover a new problematic weed on the farm that can still be contained, aggressively manage the infestation to control the population and prevent seed production. As an example, if Palmer amaranth was recently introduced and only a few dozen plants are identified in a field, remove them by hand to prevent the weeds from reproducing and spreading. If the plants are flowering, carefully remove and bag the entire plant being careful not to spread seeds. For these small infestations, burn or bury plants outside the field deep enough to prevent survival. If a resistant weed population has become more widely established on the farm, consider all appropriate options, based on the characteristics of the species, to drive down the weed infestation over time and maintain successful and profitable crop production (Figure 4).

Section 2 (cont.)


Moldboard Plowing


Row Cultivation


Hand Removal of Palmer Amaranth


Planting Green with Cover Crops


Herbicide Application


Harvest Weed Seed Control


Crop Rotation


Cleaning the Equipment to Prevent the Spread of Weeds

Figure 4. Examples of IWM practices to manage herbicide-resistant weeds. (Photo credits: Claudio Rubione, GROW)

Section 3. How do herbicide-resistant weeds spread?

Herbicide-resistant weeds spread or invade new areas just as non-resistant weeds do. The mechanisms of new weed invasion and spread fall into two main categories:

Mother Nature and Weed Biology. This includes spread by wind, water, and wildlife, and some weed species have specialized traits that help their seeds disperse naturally by these methods (Figure 5). These specialized traits can include a feathery pappus attached to each seed giving flight (horseweed and dandelion are examples), and seeds covered in barbs or burs that easily attach to the fur of animals (examples include common cocklebur and common burdock). Other examples include seeds that can pass through animals intact and potentially remain viable (includes many different species), and finally the tumbleweeds like kochia and Russian thistle that when mature break free traveling end over end spreading their mature seeds.

Human Activities. These include moving weed seeds or other plant parts with farm inputs like crop seeds, soil, manure, and compost, as well as using farm equipment or transporting freight that may be contaminated with herbicide-resistant weed seed. Using certified crop seed, regularly cleaning farm equipment, and properly composting manure and other organic waste products helps avoid moving weed seeds with these activities.

To learn more about how herbicide resistant weeds spread, visit this GROW webpage: https://growiwm.org/how-herbicide-resistant-weeds-spread/.

Horseweed has small seeds and a tuft of hairs (pappus) that allow it to disperse with the wind. (Photo credit: Claudio Rubione, GROW)

Curly dock seeds float and can be dispersed with water. (Photo credit: Claudio Rubione, GROW)

In the above picture, common pokeweed infests a no-till corn field. The berry-like fruits are often consumed by birds which then disperse the seeds while flying or roosting. (Photo credit: Penn State University)

Section 3 (cont.)

Common cocklebur seeds have barbs that attach to animals, clothing, etc. (Photo credit: Claudio Rubione, GROW)

Kochia "trail" from tumbling via wind across a field in Kansas (Photo credit: Vipan Kumar, Cornell University)

Seeds of puncture vine transported on pickup truck tires (Photo Credit: Rui Liu, Washington State University)

Figure 5. Seeds dispersing and/or spreading via natural processes and human activities.

Evolution of and selection for herbicide resistance. Herbicide-resistant individuals may be present in a weed population initially at exceptionally low frequency. With repeated application of the same herbicide or herbicide group over time, the resistant weed biotype(s) become more prominent. As an example, the widespread adoption of Roundup Ready corn, soybean, cotton, and sugarbeet allow frequent applications of glyphosate. If these crops are grown in rotation, glyphosate may be applied every season, and sometimes multiple times within a season. In addition, glyphosate is commonly used to control weeds before planting or after harvest and also during fallow periods in between crops in the western US which can further impose selection pressure for evolution of glyphosate resistance.

Importing and introducing herbicide-resistant weed seeds from an infested area to your farm is more common today. Weed-seed contaminated livestock, crop seed, animal feed, hay, manure, soil, and farm equipment all pose potential risks when moving these items between states, counties, farms, and even fields. Use certified crop seed or certified weed-free hay, and fully inspect items that are brought onto the farm to avoid bringing infested inputs onto your farm. Pay particular attention to crop seeds and hay that are grown in regions where problematic resistant weeds are common. For example, herbicide-resistant Palmer amaranth was first discovered on a few farms in Pennsylvania in 2013 and in New York in 2020. But these resistant biotypes had not "evolved" in Pennsylvania or New York; rather, they were imported into these states from the South and Midwest, likely via several different carriers, including livestock feed and farm machinery.

At least seven states have added Palmer amaranth to their Noxious Weed lists to prevent the spread (Figure 6). Without aggressive management, once a resistant biotype is introduced, it can spread throughout the farm, onto neighboring farms, and across the state and the region. With today's national and global agriculture networks, the potential for introducing new pests to the farm is greater than ever. t is critical to monitor crop and livestock inputs, farm fields, and adjacent areas to ensure you do not import and introduce something that will become a future problem.

Section 3 (cont.)

Figure 6. Palmer amaranth has been added to Noxious Weed Lists in at least seven states in the last few years including DE, IA, MD, MN, ND, OH, & PA. (Photo credit: Claudio Rubione, GROW)

Section 4. How do I select good herbicide options?

Herbicides are important tools for weed management, but managing herbicide resistance requires knowing a little more about how active ingredients interact with weeds, as well as other integrated weed management strategies. To help users understand how herbicides control weeds, **Herbicide Group Numbers** are found on the herbicide labels and containers (See Figure 7). These herbicide group numbers correspond with individual herbicide modes of action (MOA) (see **The Basics of Herbicide Resistance** for more details). Effective herbicide-resistance management must include rotating herbicide MOA, using multiple effective MOA, and reducing weed exposure to herbicides by integrating multiple management strategies that prevent weed-crop competition and weed seed production. Here is a list of herbicide management considerations to help delay and manage herbicide resistance.

1. Know herbicide MOA group numbers when making herbicide selections, and use multiple effective MOA and rotate MOA within and between growing seasons. Cross resistance within a herbicide MOA is common, so the need to select alternative effective MOA is paramount (See the Take Action Herbicide Classification Chart at https://growiwm.org/take-action-classification-chart/).

2. Consider the potential for metabolic resistance in the weeds you are targeting along with the selected herbicide partners (see Sections 8 and 9 in **The Basics of Herbicide Resistance**).

3. Use full labeled rates with multiple effective herbicides (and MOA) and start clean (plant into a weed-free seedbed).

4. Include effective residual herbicides for soil applications.

5. Include overlapping residual herbicides with postemergence applications. Overlapping herbicides should target the same weeds with different MOA's.

6. Make timely applications to small annual weeds using appropriate nozzles, spray volume, adjuvants, etc, once weeds are emerged.

7. Monitor fields regularly and scout 7-10 days after postemergence applications to evaluate weed control.

A number of weed species are usually present in any field, and herbicides are typically used to manage both susceptible and resistant biotypes. Herbicide selection depends on a number of factors (see list below) that should include resistance management. It is difficult if not impossible to select multiple effective MOA for every weed species present in a field. However, this tactic is highly recommended for known resistant biotypes and weeds that have high potential to evolve herbicide resistance (see **The Basics of Herbicide Resistance** for more details - https://growiwm.org/herbicide-resistance/). Avoid the repeated use of the same MOA every year and especially multiple times per season.

Section 4 (cont.)

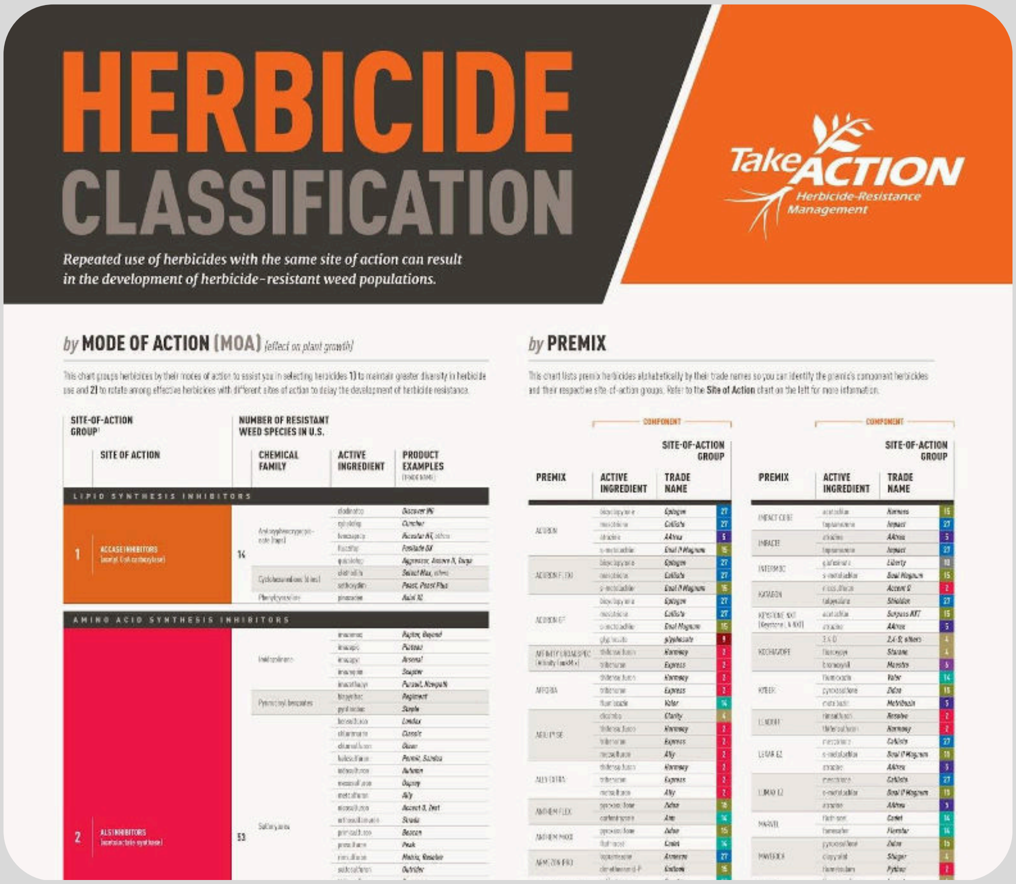


Figure 7. The Take Action Herbicide chart classifies herbicide active ingredients by their modes of action (MOA) and sites of action. (Chart credit: USB/Take Action). Chart URL: https://growiwm.org/take-action-classification-chart/

For greater detail about more general considerations for selecting appropriate herbicides, review your state and regional weed control guides (The Mid-Atlantic, Ohio, Indiana, Illinois, and Missouri, Tennessee, Michigan, and Kansas weed control guides are provided as example references in the Citations section of this webpage).

Factors to consider when selecting herbicides in addition to Managing for Herbicide Resistance

- Application timing (pre vs. post)
- Application method (broadcast vs. targeted)
- Weed control spectrum and crop safety (grass, broadleaf, etc.)
- Herbicide effectiveness (e.g., excellent, good, fair, poor)
- Herbicide tank-mix compatibility when combining multiple pesticides and additives.
- Herbicide mobility in plants (systemic vs. contact)
- Agronomic considerations (rotation restrictions, compatibility with no-till and cover crops, need for incorporation such as mechanical and/or rainfall/irrigation, etc.)

Section 4 (cont.)

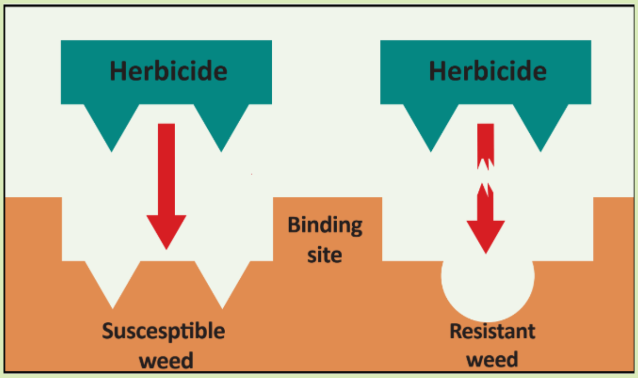
- Environmental considerations (weather conditions, especially temperature, humidity, and wind conditions during and after application, drift potential, leaching and runoff, endangered species restrictions, etc.)
- Convenience (formulation, packaging, compatibility)
- Cost and availability

Figure 8: Both herbicide-susceptible and resistant weed species can coexist in the same field. Choosing the best integrated weed management strategy is key for long-term success. (Photo credit: Claudio Rubione, GROW)

Making herbicide applications when weeds are still small enough to be controlled is crucial for optimum weed control. When that doesn't happen, weed regrowth is possible, such as the situation above, with these Palmer amaranth plants regrowing after a late postemergence application. (Photo credit: Claudio Rubione, GROW)

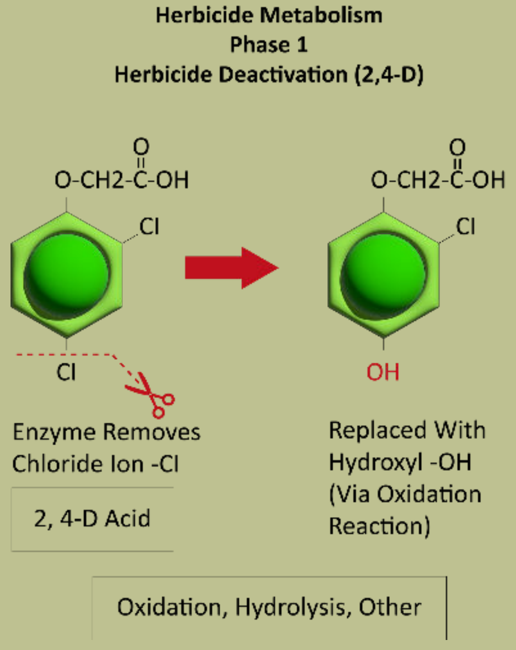
Section 5. How do I manage target-site vs. non-target site resistance?

There are many ways that weeds evolve resistance to herbicides, but the mechanisms fall into two main categories, 1.) target-site resistance (TSR) and 2.) non-target site resistance (NTSR). TSR occurs when the herbicide can no longer bind to the site of action (Figure 10a), while NTSR occurs when a mechanism prevents lethal or toxic levels of the herbicide from reaching the intended site where the herbicide "acts." Enhanced metabolism is one of the most concerning types of NTSR and leads to alteration and inactivation of herbicides (Figure 10b). (**See Section 8** in **The Basics of Herbicide Resistance** for more details - https://growiwm.org/herbicide-resistance/).



a. Target-site resistance occurs when the herbicide no longer binds to the site of action, which renders the herbicide ineffective. (Illustration adapted by W. Curran from University of Minnesota Extension; Graphic credit: Lourdes Rubione)

Figure 10. Examples of (a) target-site vs. (b) non-target site resistance in plants.



b. In the first step in herbicide metabolism, a type of non-target site resistance, the herbicide is altered. In this example, 2,4-D is inactivated when an enzyme removes a chloride ion (CL) replacing it with an hydroxyl (OH). (Image credit: William Curran, Penn State University; Graphic credit: Lourdes Rubione)

In most cases, it can be difficult to know whether the resistance mechanism at the farm level is TSR or NTSR. Regardless of the mechanism, rotating herbicide modes of action and using multiple effective modes is always important for managing resistance evolution. In addition, effective non-chemical control strategies that emphasize prevention, cultural, mechanical, and biological tactics must be implemented.

Rotating herbicide MOA and using multiple effective herbicide MOA is important for managing resistance evolution. (For more information about herbicide rotation and mixing guidelines, refer to Section 6. that follows).

Section 5 (cont.)

In addition, non-chemical management tactics are not affected by herbicide-resistance mechanisms, so they are critical for long-term weed management.

Target-site resistance has historically been the most common mechanism identified in resistant populations and the most widely studied. This type of resistance occurs when the herbicide can no longer bind to the site of action (Figure 8a). Using herbicides with different effective MOA (tank-mixing, rotating herbicides and using overlapping residuals) is widely promoted to help prevent this dominant type of resistance.

Recently, some research has raised questions about the effectiveness of rotating herbicide MOA in slowing resistance evolution. Australian and Canadian scientists point out that new research suggests herbicide mixtures or sequential applications to the same weed tend to be more effective than herbicide rotation in preventing and managing target-site resistance (Fig. 11). As an example, research conducted at the University of Illinois with glyphosate-resistant waterhemp reported that using multiple effective MOA when tank-mixing was more effective than rotating herbicide MOA in delaying resistance evolution. While these results came from TSR to glyphosate in waterhemp, it is unclear whether these results are applicable to other resistant weeds and herbicides. For herbicide mixing to be most successful, different effective modes of action must be employed at the same time.

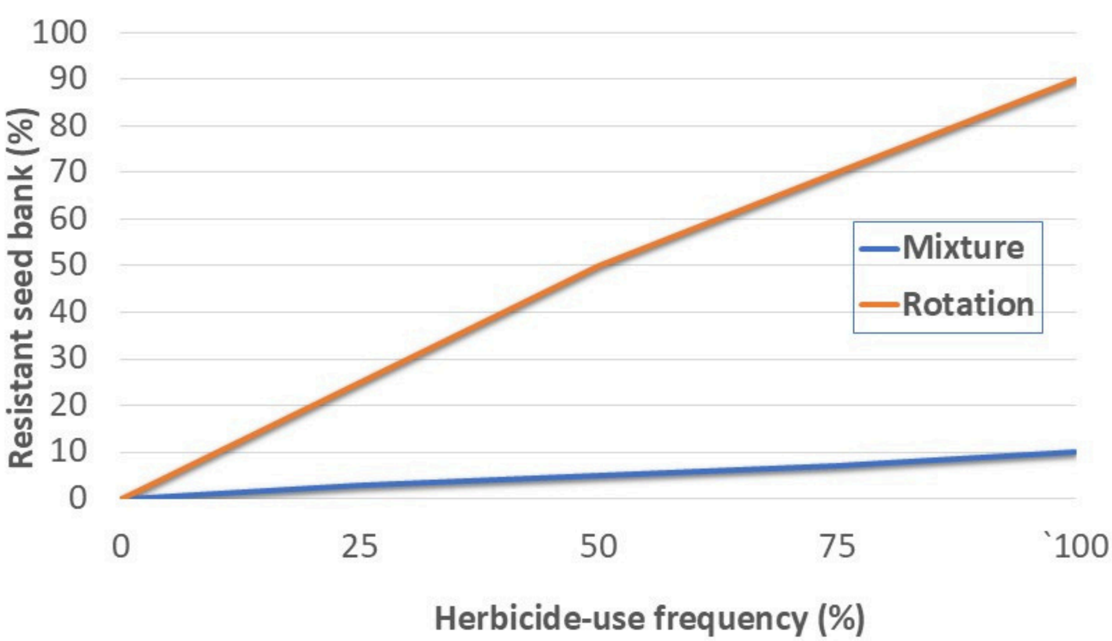


Figure 11. Effect of herbicide mixtures versus herbicide rotations on the evolution of herbicide resistance. In this example, based on simulation modeling as well as experimental evidence, a herbicide mixture using groups 2, 4, and 5 herbicides was compared to using a group 2 herbicide one, two, or three times over 4 years on the evolution of Group 2-resistant field pennycress in western Canada. (Chart adapted from Beckie and Reboud)

Section 5 (cont.)

Non-target site resistance occurs when a mechanism prevents the herbicide from reaching the intended site where the herbicide "acts" in sufficient lethal quantity. Enhanced metabolism or metabolic resistance is one of the most concerning types of NTSR and is a process within resistant (and tolerant) plants that leads to alteration and inactivation of herbicides (Figure 10b).

Using multiple effective MOA is still a common resistance management recommendation for NTSR, because the probability that a weed will evolve resistance to two different herbicide MOA when used in combination is less likely than the weed evolving resistance to a single herbicide mode. However, the benefit of using multiple effective MOA and rotating herbicide MOA to help manage NTSR resistance is likely limited, because the mechanisms for resistance can be broad-based and cross multiple herbicide groups. As another study conducted at the University of Illinois points out, in many cases, NTSR weed populations may be resistant to multiple MOA and able to survive herbicides from the same and different herbicide groups, including those the weed populations have never yet encountered. In fact, research published in Europe focusing on blackgrass (Alopecurus myosuroides) suggested that while herbicide mixtures reduced the potential for TSR, they might favor the evolution of "generalist resistance mechanisms" such as metabolic resistance.

For mixtures to be effective for resistance management, the Australian team further states they must meet strict standards. Those include providing redundant control of the target weed with multiple herbicide MOA and possessing similar soil persistence or residual activity. These criteria ensure that targeted weeds are always exposed to multiple effective MOA whether they are soil- or foliar-applied.

It is also important to know the multiple resistance status of weed populations in specific fields to inform herbicide use strategies in mixture and in rotation. For example, what is the prevalence of resistance between Group 3 (microtubule inhibitors) and Group 15 (long-chain fatty acid inhibitors) herbicides in rigid ryegrass (Lolium rigidum), the most common weedy annual ryegrass in Australia. Groups 3 and 15 have different MOA and also typically different modes of metabolism in rigid ryegrass. Differing modes of metabolism mean that different enzyme pathways detoxify the herbicides belonging to each group (Cytochrome P450 vs. Glutathione-S-Transferase enzyme families), helping to reduce the potential for multiple NTSR (Figure 12). Identifying these relationships and building herbicide programs based on both herbicide MOA and mode of metabolism or detoxification will be important in the future to prevent the evolution of multiple resistance.

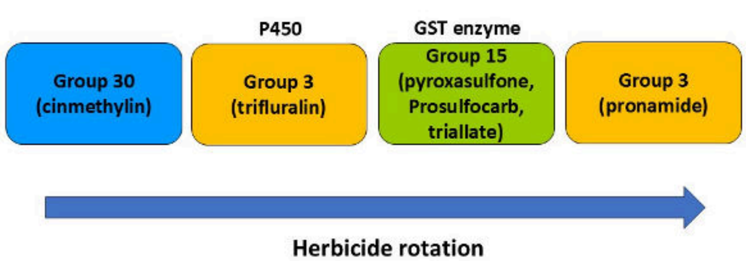


Figure 11. Effect of herbicide mixtures versus herbicide rotations on the evolution of herbicide resistance. In this example, based on simulation modeling as well as experimental evidence, a herbicide mixture using groups 2, 4, and 5 herbicides was compared to using a group 2 herbicide one, two, or three times over 4 years on the evolution of Group 2-resistant field pennycress in western Canada. (Chart adapted from Beckie and Reboud)

Section 5 (cont.)

Finally, unfortunately with enhanced metabolism, the potential for cross and multiple resistance without exposure to specific or multiple herbicide groups is a real concern. To prevent metabolic resistance, University of Illinois scientists state that new tactics and technology must be developed that will require a greater emphasis on non-chemical weed management. In addition, they recommend developing predictive tools for herbicide management and rotation recommendations based on multiple-resistance potential. Additional details are available at https://doi.org/10.1002/ps.7728.

Watch this GROW video from University of Illinois weed scientist Dr. Patrick Tranel for an overview of the dynamics between tank-mixing and herbicide rotation discussed above: https://youtu.be/N2PR0pKfTD8?si=UDr7X0MEPCIWHr_f.

Section 6. How important are herbicide rotation and tank-mixing?

The recommendation to rotate herbicide MOA and use two or more effective MOA in tank mixtures has been a common theme promoted by agricultural professionals to delay resistance. The probability that a weed will evolve resistance to two different herbicide MOA when used in combination is less likely than the weed evolving resistance to a single herbicide MOA. In addition, rotating MOA during and between seasons reduces exposure to the active ingredient and the potential selection pressure it imposes. In the example that follows (Table 1), of the three weeds targeted, only Palmer amaranth is treated with two effective MOA.

Herbicide	Weed Species: Giant foxtail	Common ragweed	Palmer amaranth
	------------------ % Control		------------------
Prod. A (group 15)	**90***	60	**85**
Prod. B (group 5)	60	**85**	**90**
# effective SOA's	**1**	**1**	**2**

*Effective products are equal or greater than 80% control and shown in bold.

Table 1. Introduction to multiple effective modes of action.

Successful use of multiple effective MOA to help manage and delay herbicide resistance depends on the lack of weed population biotypes already resistant to herbicides from certain groups. As an example, in Table 2, without resistance, several effective herbicide MOA can be used to control susceptible waterhemp. However, as multiple resistance becomes more problematic, effective herbicide modes of action become limited. Without resistance, there are herbicides from seven mode of action groups that can target waterhemp. However, if you encounter six-way resistant waterhemp which has been identified in at least two U.S. states, only glufosinate (Group 10) remains to help control the six-way-resistant biotype. The presence of multiple resistance in some of our most problematic weed species has already greatly reduced our ability to use herbicide selection tactics effectively for resistance management.

Section 6 (cont.)

Resistant MOA[1]	Group 2	Group 4	Group 5	Group 9	Group 10	Group 14	Group 27	Ineffective MOA due to resistance	Effective MOA
None								0	7
Group 9								1	6
Group 2, 9								2	5
Group 2, 5, 9								3	4
Group 2, 5, 9, 14								4	3
Group 2, 5, 9, 14, 27								5	2
Group 2, 4, 5, 9, 14, 27								6	1

Example herbicides for each group: Group 9 = glyphosate; Group 2 = chlorimuron or nicosulfuron; Group 5 = atrazine or metribuzin; Group 14 = fomesafen or saflufenacil; Group 27 = mesotrione or isoxaflutole; and Group 4 = dicamba or 2,4-D.

Table 2. Effectiveness of seven different MOA groups for control of herbicide-susceptible and herbicide-resistant waterhemp in corn or soybean. Waterhemp ranges from susceptible to having six-way herbicide resistance. Six-way multiple-resistant waterhemp has been identified in Missouri, Minnesota, and Illinois and five-way cross resistance in Ontario, Canada, and North Carolina.

Recent research on tank-mixing versus rotating herbicide modes of action has shown new light on which strategy is most important for preventing herbicide resistance, including target-site and non-target-site resistance. For an overview of this, watch this GROW video with University of Illinois weed scientist Dr. Patrick Tranel: https://youtu.be/N2PR0pKfTD8?si=34nXD8u9DxMxAANd.

See “Beyond Herbicide Site of Action: Considering “Effective” Sites of Action” for additional information on strategies for mixing effective herbicide modes of action.

Section 7. What non-chemical strategies are available and helpful?

Non-chemical strategies include prevention tactics, cultural production practices, mechanical systems, and biological tools. Limiting sunlight from reaching a weed is one of the most basic but important tools for weed control. To accomplish this:

1. Use cultural production practices that encourage the development of a quick, dense crop canopy or cover crop stand to help shade and suppress weeds. See GROW's **Cultural Production Practices webpage** for additional information on production practices that can aid weed management.

2. Add crops with different planting dates to your rotation, particularly crops that have different life cycles (i.e. fall-seeded, early-spring seeded, summer seeded).

3. If possible, selectively include tillage when you can target specific weed problems such as perennials or by burying the seeds of summer annuals.

4. Be sure to control weed escapes prior to seed set to reduce future weed populations and prevent resistant weeds from spreading. This may require walking fields and using hand removal which was common before the introduction of herbicide-resistant crops. If seed heads are present, remove plants by hand, bag them, and dispose of them outside the crop field by deep burial or burning. For larger infestations, consider adopting some newer technology such as weed electrocution and inter-row mowing (https://growiwm.org/mowing-zapping-and-outcompeting-weeds-opportunities-and-tradeoffs/) as well as **harvest weed seed control** tactics that include chaff lining or using seed impact mills.

5. Reduce the introduction of weed seed into crop fields by managing field edges with mowing or spot spraying and clean equipment between problematic fields and clean fields, so you don't spread the problem.

6. Harvest problem fields or weedy areas last to prevent the spread into other fields.

7. Clean farm equipment, including the **combine**, regularly to reduce seed spread.

For more information, visit the **GROW Weed Management Toolbox** (https://growiwm.org/weed-management-toolbox/), and see Section 4 in the **Basics of Herbicide Resistance** (https://growiwm.org/herbicide-resistance/).

Figure 14. Cover cropping can be a useful alternative tool to suppress weeds. (Photo credit: Claudio Rubione, GROW)

Section 8. What innovative technologies are on the horizon?

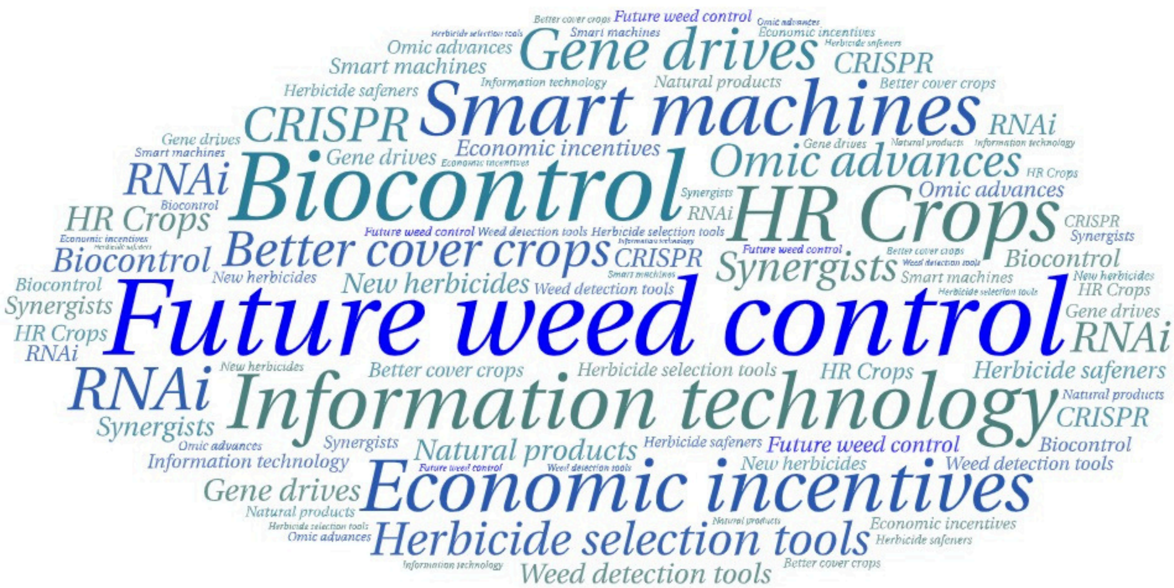


Figure 15. The future of weed management (Image credit: WordArt.com).

A number of new technologies are under development that fit into the IWM toolbox of prevention, cultural, chemical, mechanical, and biological tools, along with innovations in plant genetics and plant breeding, precision agriculture equipment and machine learning technology, information technology including the development of new decision support tools, and federal, state and private third party incentives that promote diversity in agriculture (Figure 13). Finding new cost-effective tools for agronomic weed control are challenging, but many private companies and universities around the world are actively looking for methods to help farmers manage weeds.

In addition, what can we expect from new herbicide MOA or other chemical-based strategies? Some of the major herbicide manufacturers have increased efforts to discover new herbicide molecules. Both private and public institutions are looking for naturally occurring or novel compounds that could be developed into effective commercial herbicides. Companies identify critical new enzymes and search for molecules that inhibit them, thus targeting enzymes that have not been targeted previously. See Section 10 in **The Basics of Herbicide Resistance** (https://growiwm.org/herbicide-resistance/) for more details.

1. Advances in genetics and plant breeding will likely change the way we manage pests. That includes genetic engineering and gene drives (a tool that forces certain genes to be in a species' population that could impact their success and survival). It also encompasses the "general omics" – various disciplines in biology (including genomics, proteomics, metabolomics, transcriptomics) that impact the structure, function, and dynamics of organisms. Advances could also improve crop competition and better understand light quality interactions and plant response.

Section 8 (cont.)

Certainly better cover crops could be part of this with a focus on adding regionally adapted species and cultivars, as well as mixtures of species that perform needed functions such as winter-hardy cover crops, species with enhanced allelopathy and weed suppression, and perhaps cover crops developed by plant breeders for other desirable traits.

Figure 16. The Cover Crop Breeding Network selects for winter hardiness, early vigor, high biomass, disease resistance, flowering time, seed yield, pod retention, and soft seed across 25 U.S. locations, in cover crop species such as the crimson clover shown here. (Photo credit: Claudio Rubione, GROW)

2. New precision ag equipment and machine learning technology is rapidly advancing in agriculture. This includes precision ag technologies such as **weed detection technology**, robotics, and AI-driven applications.These advancements can be applied to mechanical and chemical weed control technology. Learn more about this field on **GROW's Precision Weed Management** page (https://growiwm.org/what-is-precision-weed-management/).

Figure 17. The OAK-D multisensor camera, being tested by GROW, combines an RGB camera for object detection and identification, with a stereo camera that provides depth mapping capability. Combined with computer vision models trained on large image datasets for individual crop and weed species, the OAK-D allows for the estimation of plant density and biomass at the species level. (Photo credit: Claudio Rubione, GROW.)

Section 8 (cont.)

3. Don't forget **biocontrol**. This area continues to advance, particularly for invasive species management in rangeland and natural areas, but also in crop production. New microbial bioherbicides, predatory insects and plant pathogens, and other new discoveries are constantly being sought and tested to help manage weeds and other pests where other control tactics are limited.

4. Though not a "new" tool, **information technology** or new ways to communicate and educate are rapidly advancing. Computer-driven applications such as social media platforms deliver information to far-flung audiences from multiple sources rapidly every day. Decision Support Tools are being developed to help better manage problem weeds like Palmer amaranth. This trend will likely only intensify with advancements in artificial intelligence and other information processing technology.

5. Finally, **federal, state and private third party incentives** that promote diversity in agriculture could help with IWM efforts. These include incentives encouraging cover crop adoption, promotion of more diverse crop rotations, novel equipment adoption, area-wide pest management implementation, and other tactics to increase cropping system diversity and reduce reliance on herbicides. This should come from both public and private sectors focused on U.S. agriculture.

Section 9. How can I develop an IWM strategy?

Figure 19. On the left, redroot pigweed has not been controlled after six years of using herbicides as the sole weed management strategy. On the right, in the same period of time, the field was managed with cover crops, harvest weed seed control and crop rotations – i.e., integrated weed management (IWM). (Photo credit: Claudio Rubione, GROW)

To develop an IWM strategy on your farm, consider using the **GROW Weed Management Planner** (https://growiwm.org/the-weed-management-planner/) to help identify useful strategies for your weed spectrum**.**

The Weed Management Planner was developed for the Mid-Atlantic region, but has relevance for growers across other parts of the U.S. Corn and Soybean Belt. Additional versions that focus on other regions and cropping systems should be available in the future. The current tool will help you identify common crop management and weed control strategies that can have a positive effect in managing your biggest weed problems, as well as those that could worsen certain weed infestations.

Here is an example scenario developed using the GROW Weed Management Planner.

A hypothetical farm is located in the Southern Corn Belt and grows corn and soybean in rotation, using no-till practices. The farm has problems with glyphosate- and ALS-resistant (Group 2) horseweed (marestail) and increasing problems with glyphosate- and ALS-resistant waterhemp. Additional (non-herbicide-resistant) weeds include common lambsquarters, common ragweed, and giant foxtail.

Section 9 (cont.)

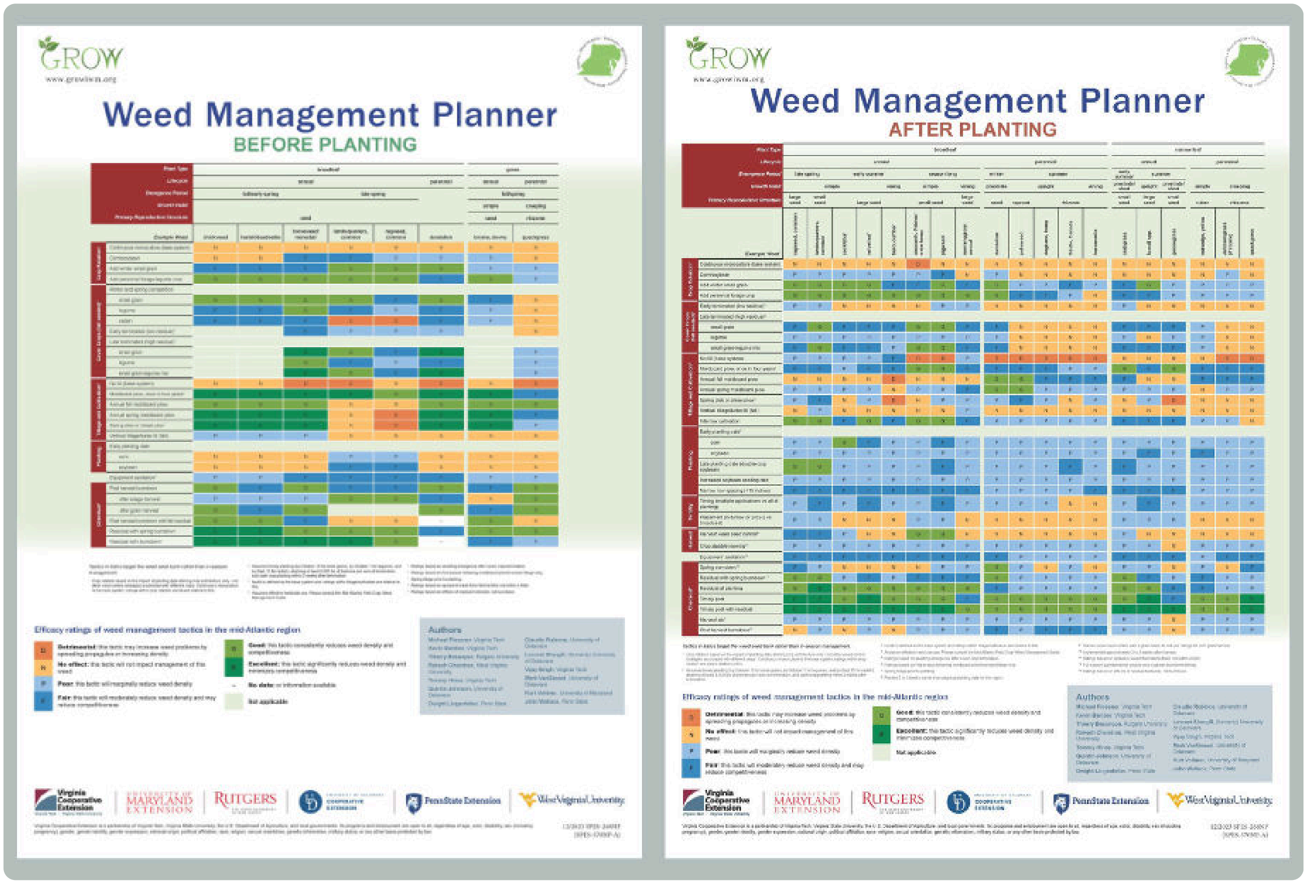


Figure 20. The Weed Management Planner is divided into two sections, one outlining common crop and weed management tactics BEFORE planting (left), and one listing those employed AFTER planting (right). Weed Management Planner URL: https://growiwm.org/the-weed-management-planner/

A. Effective cultural production practices:

- Add a perennial forage crop such as alfalfa to the rotation. Generally, alfalfa is grown for three or four years with frequent mowing during the growing season. This would reduce or perhaps eliminate some of these annual weed species. (Unfortunately, adding a perennial forage to an annual grain rotation is often difficult because of the need for additional equipment, time, labor, and access to livestock and/or markets).
- Seed a small grain cover crop such as cereal rye after corn harvest. This will require timely corn harvest to allow cereal rye seeding. In the Southern Corn Belt, harvest corn by early or mid-October in order to achieve successful cereal rye growth for weed suppression. This will directly compete with horseweed and other winter annuals, thus reducing the density and vigor of surviving plants. Terminate the rye cover crop as late as possible in the spring to increase biomass production. The persistent mulch biomass will help suppress the waterhemp as well as the other summer annual weeds.
- Add winter wheat or another winter cereal cash crop to the rotation. This will help reduce the success of both winter and summer annual weeds and bring additional management opportunities to the operation...

Section 9 (cont.)

- ...In the Southern Corn Belt, double-crop soybeans are common after winter wheat or barley. The cereal grain also provides additional opportunity to establish late summer or fall cover crops.
- Reduce row spacing for appropriate crops such as soybean where feasible. Row spacing is proven to lower the impact of certain weeds by aggressively competing for light and other resources with weed species. See this GROW video on row spacing for more information: https://youtu.be/L4UMXLLD9Qk?si=aPR50amXPnVNFCTe

Figure 21. Row spacing is a powerful tool to reduce both the number and size of weeds. (Photo credit: Penn State University)

B. Effective mechanical control tactics:

- Primary tillage in the spring will control horseweed. This can range from moldboard plowing to using a heavy disk or field cultivator depending on residue levels in the field. Annual tillage is less effective on waterhemp, but in a no-till system, strategically targeted moldboard plowing (inversion tillage) once in four or five years can bury seed and reduce weed density in subsequent years. This would also benefit control of the other annual weeds. Refer to GROW's Tillage, Cultivation and Mowing page (https://growiwm.org/mechanical-weed-control/) for additional information.
- Include **inter-row cultivation** or **mowing** to help manage weeds after emergence. Although cultivation is much less common in no-till systems, **high-residue machines** are available that are equipped with wide sweeps to cut and control weeds between crop rows. In conventional tillage systems, a number of different types of inter-row weed control tools can be employed to help manage emerged weeds.
- Adopt Harvest Weed Seed Control (HWSC) strategies in soybean to help manage waterhemp and some other summer annual weeds.
- Manage field edges and fencerows with mowing to prevent these annual weeds from successfully adding more seeds to the seedbank..

Section 9 (cont.)

Figure 22. Inter-row cultivation has been a long-time mechanical weed control practice for many farmers (Photo credit: Claudio Rubione).

C. Effective chemical tactics:
It is difficult to select **multiple effective herbicide MOA** for every weed species present in a field. However, this tactic is highly recommended for known resistant biotypes and weeds that have high potential to evolve herbicide resistance. In this example, herbicide-resistant horseweed and waterhemp are the driver weeds. However, when choosing the herbicide programs, be sure to also consider the other weed species present. Selected herbicides below are based on the **2024 Mid-Atlantic Weed Control Guide**. Review state or regional weed management guides and a current herbicide label for detailed herbicide use recommendations.

For glyphosate- and ALS-resistant (Group 2) horseweed, use an effective burndown program with two or more effective herbicide modes of action and also include effective residuals. Example burndown herbicides for soybean include 2,4-D, dicamba (dicamba-resistant soybeans only), halauxifen (Elevore) (Group 4), and saflufenacil (Group 14). Effective residuals for waterhemp include metribuzin (Group 5), sulfentrazone and flumioxazin (Group 14) and S-metolachlor (Group 15). A number of products are available that contain these single and multiple active ingredients. For corn, burndown herbicides include 2,4-D and dicamba alone or in combination, usually mixed with a residual herbicide such as atrazine or simazine, isoxaflutole, S-metolachlor, mesotrione, or other premixes containing these plus other active ingredients.

For glyphosate- and ALS-resistant waterhemp, use effective residual herbicides at planting and timely postemergence applications that include effective residuals.

In soybean, effective residual products can include S-metolachlor and pyroxasulfone (Group 15), metribuzin (Group 5), and fomesafen, sulfentrazone, and flumioxazin (Group 14). A number of products are available that contain these single and multiple active ingredients and some of these can be applied postemergence.

Section 9 (cont.)

Effective postemergence herbicides for the resistant waterhemp in this example include 2,4-D (Group 4 for Enlist soybean), glufosinate (Group 10 for Enlist, XtendFlex, and LibertyLink soybean), and lactofen, fomesafen, and acifluorfen (Group 14).

For corn, effective residual herbicides for the resistant waterhemp in this example include atrazine and simazine (Group 5), S-metolachlor and pyroxasulfone (Group 15), acetochlor/atrazine mixtures and S-metolachlor/atrazine mixtures (Group 15/5) that can include mesotrione and bicyclopyrone (Group 27) and other active ingredients. Effective postemergence herbicides in corn include atrazine (Group 5), and mesotrione, topramezone, tembotrione, and tolpyralate (Group 27), glufosinate (Group 10) and dicamba (Group 4) containing products.

Developing an IWM Strategy – bringing it home. In this Southern Corn Belt scenario, several of these IWM tactics can have a dramatic impact on herbicide-resistant weed management.

For example, let's say that by owning or borrowing a grain drill, the farm incorporates a rye cover crop after corn harvest, after learning the benefits obtained by cover crop adoption, including suppression of two important herbicide-resistant weeds. At soybean planting time, the farm modifies/improves the soybean planter to successfully plant green into the cover crop, which allows the cereal rye to achieve more biomass and thus weed suppression. With a second planter or one with split rows, the farmer narrows the soybean row spacing to 15 inches to help further suppress weeds and carefully chooses the herbicide program based on multiple effective modes of action.

After soybean harvest, the farmer plants a winter wheat cash crop using the grain drill to help diversify the crop rotation, which has many benefits. Now with both soybean and wheat, the farm could consider adopting harvest weed seed control (HWSC), by either modifying the combine for chaff lining or adding a seed impact mill to the combine. This would help reduce the waterhemp and other summer annual weed seedbank in soybean as well as some winter annual weeds in wheat. In addition, after wheat harvest, the farmer could seed another cover crop in late summer, such as hairy vetch plus a small grain to help suppress winter annual weeds (such as horseweed) and also provide additional nitrogen for the subsequent no-till corn crop.

Alternatively, the farmer could seed a perennial forage crop like alfalfa after wheat harvest adding yet another crop to the rotation and a very powerful weed control tactic that uses repeated mowing. Additional equipment, labor, and markets will be required for this type of big change, so consider options carefully. Finally, the farmer selects the rotational corn crop herbicide program based on multiple effective modes of action as well as other herbicide selection factors. All these IWM tactics are possible, and others could also be considered. So, what weed management strategies best fit your farm operation and need for better weed control? Please share your opinion with us here: emilysu@vt.edu.

Section 10. How are other farmers using IWM?

GROW's Farmer Case Studies page contains video interviews with farmers across the country who are experimenting with or have mastered the use of multiple integrated weed management tactics to control weeds on their operations. Visit the webpage to learn more: **https://growiwm.org/farmer-case-studies/**.

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CITE AS: Curran, W., Rubione, C., Unglesbee, E., VanGessel, M. (2024) How to Manage Herbicide Resistance with IWM. Getting Rid of Weeds (GROW) Through Integrated Weed Management. www.growiwm.org/how-to-manage-herbicide-resistance-with-iwm/

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