Dec 1st, 12:00 AM

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Introduction

Over the last couple of decades, waterhemp has transitioned from being a relatively unknown weed species to one of the worst weeds in the Midwest (Steckel 2007). Its recent success as a weed can be attributed both to its biological characteristics and to changes in weed management practices (Costea et al. 2005). Notable biological characteristics of waterhemp include: rapid growth rate (in part due to its use of the C_4 photosynthetic pathway), prolific seed production (up to or exceeding 500,000 seeds per plant), extended emergence period throughout much of the growing season, and dioecious reproductive habit. The latter – which means that plants are either male or female – ensures that plants outcross and, thus, increases genetic diversity of the species and effectively moves genes within and among populations. The adoption of no-tillage and reduced-tillage cropping systems has favored small-seeded weedy species, such as waterhemp; these small seeds germinate most effectively when they are at or near the soil surface.

Further contributing to waterhemp's success as a weed has been its ability to rapidly evolve resistance to various herbicides (Tranel et al. 2011). Its proclivity to evolve herbicide resistance can be attributed to its biological characteristics mentioned above. Of particular importance are high seed production and genetic diversity, which provide the raw materials on which selection can act. Couple the abundant waterhemp "raw material" (i.e., its high reproductive output and genetic diversity) with the intense selection pressure provided by herbicides, and the evolutionary outcome of herbicide-resistant waterhemp populations is not surprising. The problem of herbicide-resistant waterhemp is further exacerbated by waterhemp's dioecious habit and the potential for long-distance dispersal of resistance via wind-borne pollen. Herbicide resistance easily moves between populations and can become "stacked" with other herbicide resistance traits, leading to populations with multiple herbicide resistance.

History of herbicide resistance in waterhemp

Waterhemp has thus far evolved resistance to herbicides from five different site-of-action groups (Figure 1). The initial reports of herbicide-resistant waterhemp populations were to the triazine herbicides (PSII inhibitors) and the ALS inhibitors during the early 1990s. Subsequently, waterhemp populations were identified with resistance to the PPO inhibitors (e.g., the diphenylethers) and then to glyphosate. Recently, waterhemp populations with resistance to the HPPD inhibitors were identified in both Illinois and Iowa (Hausman et al. 2011; McMullan and Green 2011).

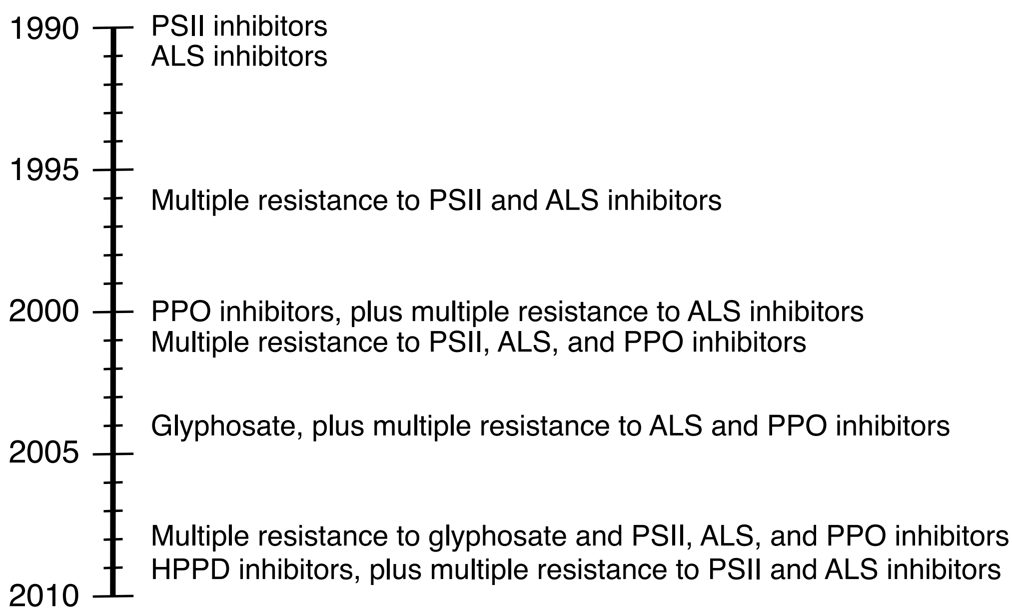

Figure 1. Timeline of resistance and multiple resistance to herbicides/herbicide groups in waterhemp (adapted from Tranel et al. 2011).

The mechanisms by which waterhemp is resistant to the five different site-of-action groups are numerous and diverse (Table 1). In some cases, waterhemp exhibits different resistance mechanisms even within a particular herbicide site-of-action group. For example, resistance to triazine herbicides may be conferred by either a resistant target site or by enhanced herbicide detoxification. Similarly, although all known cases of resistance to ALS inhibitors in waterhemp are due to an altered target site, the specific mutation present within the target site may differ among resistant biotypes.

Table 1. Mechanisms of herbicide resistance in waterhemp.

Herbicide or group	Resistance mechanism(s)	Mutation
Triazines	Resistant target site	Ser264Gly in D1 protein
	Herbicide metabolism	Unknown
ALS inhibitors	Resistant target site	Trp574Leu, Ser653Asn, or Ser653Thr in ALS
PPO inhibitors	Resistant target site	Deletion of Gly210 in PPO2
Glyphosate	Target site amplification	Multiple genomic copies of EPSPS
HPPD inhibitors	Unknown	Unknown

Multiple herbicide resistance in waterhemp

Resistance in a weed species to a single herbicide (or to a group of herbicides with a common site of action) is cause for concern. However, this typically will not present an unmanageable problem in a major crop such as corn or soybean, because multiple herbicides are labeled for such crops and, thus, alternative chemical options are available. Unfortunately, for some of our most troublesome weeds, including waterhemp, we are increasingly encountering populations that possess multiple herbicide resistance. That is, these populations possess resistance to herbicides spanning multiple site-of-action groups. In fact, as can be seen in Figure 1, all new cases of herbicide resistance in waterhemp subsequent to resistance to triazines and the ALS inhibitors were cases of multiple herbicide resistance.

For example, the first population of waterhemp identified with resistance to the PPO inhibitors also was resistant to ALS inhibitors. The first glyphosate-resistant waterhemp population also had resistance to ALS and PPO inhibitors, and both waterhemp populations reported resistant to HPPD inhibitors also contained resistance to triazines and ALS inhibitors. In the most extreme case of multiple resistant waterhemp reported to date, a single population is resistant to triazines, ALS and PPO inhibitors, and to glyphosate (Tranel et al. 2011).

Coworkers and I recently have conducted surveys to determine the extent of multiple herbicide resistance in waterhemp. We have asked producers to send us tissue samples from waterhemp plants suspected of being resistant to glyphosate. We then perform molecular tests on DNA from the tissue samples to determine if the plants are resistant to glyphosate, PPO inhibitors, and/or ALS inhibitors. We have focused on these three herbicide/herbicide groups since they represent the options for POST control of waterhemp in glyphosate-resistant soybean (and from a technical standpoint, availability of molecular tests for these three resistances enables rapid screening). Using this approach in 2010, glyphosate-resistant waterhemp was confirmed in 20 of 24 fields sampled. As expected, ALS resistant waterhemp was widespread among the fields. Less expected, however, was that a third of the fields were found to contain waterhemp resistant to PPO inhibitors. Not only was multiple herbicide resistance found at the field level, but, as depicted in Figure 2, multiple resistance also was found at the individual plant level. For example, 36% of the plants were resistant to glyphosate and ALS inhibitors, 9% were resistant to glyphosate and PPO inhibitors, and 7% were resistant to all three herbicide/herbicide groups. These data indicate that resistances to all of the major soybean POST herbicides are being stacked into individual waterhemp plants, which poses a serious threat to our ability to effectively manage this weed.

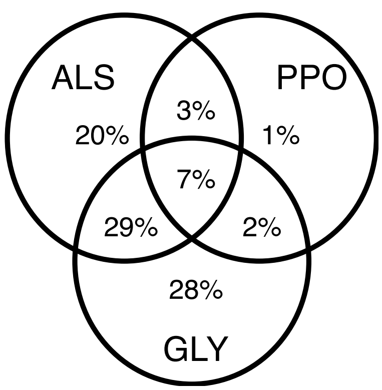

Figure 2. Venn diagram depicting the occurrence of multiple herbicide resistance to ALS inhibitors, PPO inhibitors, and glyphosate in waterhemp. The numbers indicate the percentage of plants resistant to one (in the non-overlapping part of each circle), two of the three (where two circles overlap) or all three (where the three circles overlap) of the herbicide/herbicide groups. Plant tissue from individual plants (122 total) was collected during 2010 from 24 fields suspected of containing glyphosate-resistant waterhemp. Resistant profiles of each sampled plant were determined from molecular tests. Thirteen percent of the plants were found to be sensitive to all three herbicides.

Future implications

The consensus in the weed science industry is that herbicides with new sites of action are unlikely to be commercialized in the near future. Thus, we essentially will have to make do with our current arsenal of herbicides. Multiple-resistant waterhemp will continue to expand, both in frequency at which multiple-resistant populations occur, and in the number of herbicide/herbicide groups to which populations are resistant. For example, I fully expect that a waterhemp population with resistances to triazines, ALS, PPO, and HPPD inhibitors, and to glyphosate will be identified during the 2012 or 2013 growing season. It is also expected that waterhemp will evolve resistance to herbicides from additional site-of-action groups if such herbicides are relied upon extensively for waterhemp management. In fact, a very recent report suggests a waterhemp population in Nebraska has evolved resistance to 2,4-D (Bernards et al. 2011). If confirmed, this will represent the sixth site-of-action group to which waterhemp has evolved resistance.

Perhaps the most immediate impact of multiple-resistant waterhemp will be an end to the “one-size-fits-most” approach to weed management in the Midwest. The most effective and economical weed management strategies will vary from field to field, depending on the spectrum of resistant waterhemp biotypes present in a given field. In extreme cases, selective cultivation may have to augment chemical control.

The occurrence of multiple-resistant waterhemp also will impact our ability to effectively implement resistance mitigation strategies for herbicides to which waterhemp has not already evolved resistance. For example, tank mixing herbicide A with herbicide B will not delay the evolution of resistance to herbicide B if the population is already resistant to herbicide A.

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