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Herbicide resistance in turfgrass: a chance to change the future?

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Annual bluegrass, *Poa annua* L.; goosegrass, *Eleusine indica* L. Gaertn; corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr

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Abstract

Herbicide resistance has for decades been an increasing problem of agronomic crops such as corn and soybean. Several weed species have evolved herbicide resistance in turfgrass systems such as golf courses, sports fields, and sod production—particularly biotypes of annual bluegrass and goosegrass. Consequences of herbicide resistance in agronomic cropping systems indicate what could happen in turfgrass if herbicide resistance becomes broader in terms of species, distribution, and mechanisms of action. The turfgrass industry must take action to develop effective resistance management programs while this problem is still relatively small in scope. We propose that lessons learned from a series of national listening sessions conducted by the Herbicide Resistance Education Committee of the Weed Science Society of America to better understand the human dimensions affecting herbicide resistance in crop production provide tremendous insight into what themes to address when developing effective resistance management programs for the turfgrass industry.

Introduction

Herbicide resistance has been defined as an inherited ability of a weed species to survive and reproduce following exposure to a dose of herbicide that is normally lethal to the wild type (Vencill et al. 2012). Over-reliance on herbicides as a sole measure for weed control has selected for weed populations with rare mutations that allow them to survive herbicide treatment. Some of these mutations are (1) alterations to herbicide binding sites (often within an enzyme) that prevent effective herbicide interaction with its target; (2) enhanced metabolic capacity to degrade an herbicide before toxicity is achieved; (3) altered biokinetic patterns (e.g., absorption, translocation, sequestration) that prevent an herbicide from reaching its site of action within the plant; and, specifically for glyphosate, (4) overexpression of the target enzyme such that inhibition by the herbicide is no longer effective (Heap 2014). Herbicide resistance has become a global problem in agronomic cropping systems. Reports of herbicide-resistant weeds increased from fewer than 100 unique cases in 1985 to nearly 500 in 2019; these cases span over 250 different weed species, with more reports in Poaceae than any other plant family (Heap 2019; Heap and Duke 2017).

Although the majority of these resistant species evolved in agronomic cropping systems, more than 20 unique cases have evolved in turfgrass systems such as golf courses, sports fields, and sod production. Particularly problematic resistant species in turfgrass are annual bluegrass (*Poa annua* L.), goosegrass [*Eleusine indica* (L.) Gaertn.], certain sedges (*Cyperus* spp.), and broadleaf species (Heap 2019). Much research has been conducted to verify resistance and to understand the mechanisms of resistance in these species (Binkholder et al. 2011; Brosnan et al. 2008, 2012; Brunharo et al. 2019; Derr 2002; Isgrigg III et al. 2002; Kelly et al. 1999; McCullough et al. 2016a, 2016b, 2016c, 2017; McElroy et al. 2013, 2017; Mengistu et al. 2000; Patton et al. 2018; Yu et al. 2018). Beyond site-of-action resistance, there are also reports of annual bluegrass evolving resistance to multiple mechanisms of action, as well as resistance via enhanced herbicide metabolism (Breeden et al. 2017; Brosnan et al. 2016; Syvantek et al. 2016).

Despite an abundance of research on the topic of herbicide resistance in weeds of turfgrass systems, the problem is not decreasing. A recent survey of annual bluegrass on golf courses in Tennessee found that, of randomly selected populations, 64% had some degree of resistance to glyphosate, 58% had some degree of resistance to prodiamine, and 21% had some degree of resistance to foramsulfuron (J. Brosnan, unpublished data). Continued research efforts exploring the biology and management of herbicide-resistant weeds will be needed to develop turfgrass-specific best management practices (BMPs) for resistance, similar to those outlined by Norsworthy et al. (2012) for agronomic cropping systems. The continued reliance on herbicides, without integration of other, more sustainable weed control tactics, has accelerated the evolution of herbicide-resistant weeds (Westwood et al. 2018). However, development of

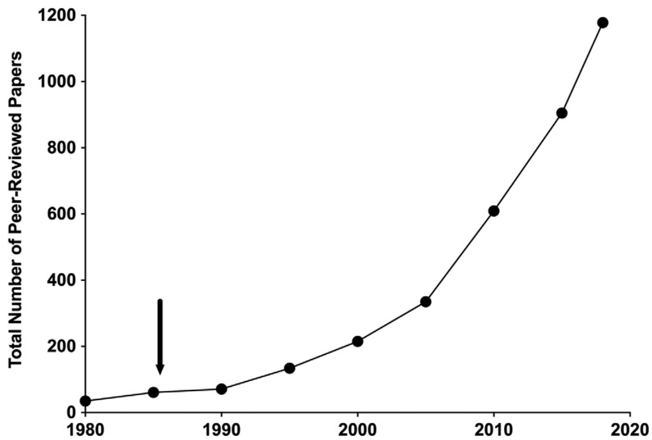

Figure 1. Total number of peer-reviewed papers on herbicide resistance in corn and soybean found in the Web of Science database as of December 21, 2018. Search parameters as follows: Topic = Herbicide + Topic = Resistance + Topic = Corn OR Topic = Soybean$_{SEP}^{L}$ + Topic ≠ Insecticide + Topic ≠ Fungicide. The total number of papers published on herbicide resistance in turfgrass as of this date (i.e., 64) is indicated by the arrow, underscoring that the current status of the problem is still relatively small in scope. Search parameters for turfgrass papers were: Topic = Herbicide + Topic = Resistance + Topic = Turfgrass + Topic ≠ Insecticide + Topic ≠ Fungicide.

BMPs will not be enough to remedy herbicide resistance problems in turfgrass; there are well-documented barriers to BMP adoption by farmers in production agriculture (Schroeder et al. 2018). Ervin and Jussaume (2014) explained that herbicide resistance will not be mitigated without addressing the human dimensions of the problem, including the social, economic, political, and cultural components. What factors do turfgrass managers take into account when selecting a weed management strategy? Is the decision driven 100% by economics, or are there other influences at play? Turfgrass weed scientists should work with social scientists to seek answers to these questions when developing herbicide-resistant weed management programs.

Call to Action

Herbicide resistance has been an increasing problem of agronomic crops such as corn and soybean for decades. There were 35 peer-reviewed reports of herbicide resistance in corn or soybean systems as of 1980; such reports steadily increased to 215 by 2000 and >1,100 as of December 2018 (Anonymous 2018; Figure 1). This increase supports the assertions of Schroeder et al. (2018) that research, extension, and educational efforts to combat herbicide resistance in agronomic crops have yielded mixed results at best. A literature search with parameters specific to turfgrass found that herbicide resistance in turfgrass is still relatively small in scope. For example, there was only a single peer-reviewed report of herbicide resistance in turfgrass as of 1995; such reports increased to 24 by 2010 and 64 as of December 2018 (Anonymous 2018; Figure 1). Skeptics may contend that this difference (>1,100 peer-reviewed reports compared with 64) is simply an effect of hectares subjected to selection pressure from herbicide treatment and the number of weed scientists working in corn and soybean compared with turfgrass. On the contrary, we feel that this difference only shows that the increase in resistance that occurred in agronomic crops is just beginning in turfgrass. This should be a call to action for those in the turfgrass industry to develop effective programs to tackle the herbicide resistance issue while the scope of the problem is still small. Resistance in agronomic cropping systems illustrates what will happen in turfgrass if herbicide resistance becomes broader in terms of species, distribution, and mechanisms of action. In short, there is still a chance to change the future in turfgrass.

What Will Be Effective?

As noted by Ervin and Jussaume (2014), understanding the human dimensions affecting herbicide resistance will be critically important in creating effective programs to help turfgrass managers, and the turfgrass industry in general, to mitigate the problem. A series of national listening sessions conducted by the Herbicide Resistance Education Committee (HREC) of the Weed Science Society of America (WSSA) was designed to gather information from farmers regarding the human dimensions affecting herbicide resistance in crop production to provide insight into what themes to address in turfgrass. A full report on the outcomes of those national listening sessions was published by Schroeder et al. (2018) and is summarized below.

Desire for New Mechanisms of Action (MOAs)

Listening sessions highlighted that farmers had a strong desire for new herbicidal MOAs to manage the evolution of resistant weeds in their fields. In four of the six regions surveyed, farmers indicated that their most pressing need for managing resistance issues was new herbicide technology, a sentiment that was consistent with previous reports and termed "techno-optimism" by Dentzman et al. (2016). Although a series of national listening sessions to gauge the sentiments of turfgrass managers has not taken place as of this writing, we have observed great interest in new turfgrass herbicides to manage resistant weeds. For example, indaziflam (WSSA Group 29), an inhibitor of cellulose biosynthesis, controls annual bluegrass with resistance to mitotic inhibitor, photosystem II (PSII) inhibitor, and acetolactate synthase (ALS)–inhibiting herbicides (Brosnan et al. 2014, 2015), as well as dinitroaniline-resistant goosegrass (McCullough et al. 2013). Turfgrass managers are also very interested in the development of methiozolin [(5-(2, 6-difluorobenzyl) oxymethyl-5-methyl-3-(3methylthiophen-2-yl)-1, 2-isoxazoline)] for annual bluegrass control (Koo et al. 2014). Grossmann et al. (2012) reported that methiozolin and cinmethylin inhibit tyrosine amino transferase (TAT). However, Campe et al. (2018) recently reported that cinmethylin, a benzylether that is structurally similar to methiozolin, inhibits fatty acid thioesterase (FAT), not TAT. They further demonstrated that FAT inhibition is a unique site of action, different from that targeted by inhibitors of acetyl CoA carboxylase and very-long-chain fatty acid synthase. Although there is debate over its exact MOA, it does appear that methiozolin has a novel MOA. Methiozolin effectively controls herbicide-susceptible annual bluegrass as well as biotypes with target site resistance to PSII, enolpyruvylshikimate-3-phosphate synthase (EPSPS), and mitotic inhibitor herbicides (Brosnan et al. 2017; Koo et al. 2014).

Despite these promising newly introduced or under-development turfgrass herbicides, it is critically important that turfgrass managers understand that these new herbicides will not control all herbicide-resistant weeds, particularly those able to survive via non–target site resistance mechanisms. For example, Brosnan et al. (2017) reported that, although methiozolin effectively controlled annual bluegrass with target site resistance to inhibitors of PSII, EPSPS, and cellular mitosis, it did not control a biotype reported to be resistant to ALS inhibitors via both target and non–target site resistance mechanisms. Turfgrass managers and weed scientists must also communicate that discovery of new herbicides with novel MOAs is a rare event and that a lack of new products is not exclusively a function of excessive regulation by those in national and/or state agencies. As explained by Duke (2012), the consolidation of the pesticide discovery industry and the increased cost of pesticide discovery have limited the discovery of new herbicides. During a symposium at the 59th Annual Meeting of the WSSA, it was reported that the cost of bringing a new herbicide to the market in 2014 was $286 million (A. Agi, personal communication). Moreover, turfgrass managers must appreciate the importance of preserving the effectiveness of current herbicides, because new herbicides will not be available for a long time at best.

Need for More Education to Aid with Diversification

Farmers communicated that there was a need for more herbicide resistance education, particularly programs targeted at individuals who did not participate in the listening sessions. Schroeder et al. (2018) detailed a sentiment among farmers that herbicide-resistant weeds moved onto their farms from neighboring fields (where farmers were not practicing resistance management). However, this opinion contradicts empirical reports by Neve et al. (2011) regarding evolution of herbicide resistance over space and time. They indicated that the main drivers for glyphosate resistance evolution were selection pressure and population size, the greatest risks being associated with the largest populations of Palmer amaranth (*Amaranthus palmeri* S. Wats.). A comprehensive presentation on the evolution of multiple-herbicide resistance in Palmer amaranth from Kansas was presented during a symposium at the 59th Annual Meeting of the WSSA (M. Jugulam, personal communication). The risks of resistance were reduced when glyphosate applications were replaced by an herbicide with another mechanism of action (Neve et al. 2011). This demonstrates the need for both diversification of management tools and reduction of weed population size.

Schroeder et al. (2018) also wrote that there was a lack of awareness among farmers regarding truly integrated weed management approaches (i.e., those incorporating non-herbicide methods), as well as a lack of knowledge regarding herbicide MOAs altogether. Additionally, there was a sentiment among listening session participants that implementing diverse weed management programs (i.e., those relying on strategies other than just herbicides) would not be possible for economic reasons. Information pertaining to nonchemical weed management programs in turfgrass systems is limited. Practices such as altering nutrient applications, alleviating soil compaction, and increasing mowing height have been shown to discourage weed infestation in turfgrass (Busey 2003). Spirited by the success of harvest weed seed control techniques in row crops, use of cultivation equipment for weed control in turfgrass has been explored recently (Brosnan et al. 2020). Whereas researchers documented reductions in annual bluegrass with a mechanical device termed a "fraise mower," they observed no reduction in the quantity of annual bluegrass seed in the soil and increased quantities of other species as well. The researchers determined that the instrument was not a replacement for timely herbicide applications but could be used as part of an integrated program.

Although turfgrass-specific listening sessions have not been conducted to date, it is likely that sentiments among turfgrass managers would be similar to those reported by Schroeder et al. (2018). Turfgrass managers combating resistance issues will most likely have a strong desire for new herbicide technologies and be hesitant to adopt nonchemical management approaches because of financial or logistical barriers. However, there is a need for adoption of sustainable practices to manage herbicide-resistant weeds. Lessons learned via the recent HREC listening sessions should serve as a call to act now and change the future of resistance problems in turfgrass, before the problem becomes more broad in scale.

Where should these actions begin? Coble and Schroeder (2016) explained that, for herbicide resistance to be managed, everyone has a role—stakeholders (i.e., turfgrass managers), the agricultural input chain network (i.e., chemical, seed, and equipment companies, as well as distributors and retailers), university weed scientists, private consultants, government agencies, regional and national organizations (e.g., for turfgrass, the Golf Course Superintendents Association of America, the Sports Turf Managers Association, the Turfgrass Producers International), as well as regional and national professional societies (e.g., the WSSA and the regional weed science societies), and the press. None of these groups operates in a vacuum; all must be held accountable for ensuring that resistance management is a central tenet of any weed control decision. Technology can certainly aid in this approach, as it facilitates social connectivity on a global scale. Of the top 500 websites visited worldwide, YouTube, Facebook, and Twitter rank 2nd, 3rd, and 11th, respectively (Alexa 2019), with users of these platforms numbering >2 billion individuals globally (Statista 2019). Coordinated efforts to place resistance management information on these platforms will result in far greater engagement than sole reliance on university field days and extension publications. Though these platforms are imperfect, they serve as valuable tools for weed scientists to distribute research-based resistance management recommendations to practitioners. There are several examples of this practice being successful in row crops, particularly the WeedSmart campaign (weedsmart.org.au) in Western Australia that provides research-based information to farmers via Facebook, YouTube, and Twitter, in addition to podcasts, webinars, and other digital materials. Another important way these platforms can be used is to connect practitioners to each other. Turfgrass managers and others could share their struggles with resistance as well as successful (and unsuccessful) strategies to deal with it.

The role of the turfgrass manager is paramount to the success of resistance management, given that they are ultimately the individuals applying herbicides that select for resistant weeds. That said, turfgrass managers are often at the bottom of the hierarchy when it comes to resistance management decisions; university weed scientists, extension personnel, and others in the industry are sending (sometimes conflicting) messages to these individuals. It is time to shift that paradigm and provide turfgrass managers who have encountered herbicide resistance an opportunity to share their stories with colleagues. The stories of those who have diversified their weed management approaches are also important for others to hear. Identifying turfgrass managers to champion resistance management and more sustainable weed management practices could lead to greater adoption than if the message is coming solely from university specialists.

Some encouraging developments have already begun to bolster resistance management efforts for turfgrass. For example, the US Environmental Protection Agency now requires herbicide registrants to list MOA information on herbicide labels, an action that will help increase understanding of product MOAs among not only turfgrass managers but also distributors and retailers (Anonymous 2017). A recent grant from the US Department of Agriculture–Specialty Crops Research Initiative (USDA-SCRI) amounts to recognition of the need for resistance management resources in turfgrass. This grant will support an integrated research and extension project involving 14 states focused on managing the nationwide epidemic of herbicide-resistant annual bluegrass (Ledbetter 2018). This project will generate a plethora of information that university weed scientists can use to develop effective educational materials on management of herbicide resistance in annual bluegrass.

Economics of Resistance Management Are Challenging

Another key theme from farmers at the recent HREC listening sessions was that the agricultural economy does not allow for adoption of the diverse weed management tactics required to combat herbicide resistance (Schroeder et al. 2018). Our hope is that the network of chemical, seed, and equipment companies can work together with distributors and retailers to create financial incentives for resistance management in turfgrass while the problem is still small in scale. Many turfgrass managers purchase herbicides via "early-order programs" that offer end-users discounted prices and delayed invoicing if they commit to purchasing products before a benchmark date. Could these programs be restructured to offer economic incentives for using variable MOAs, either applied as mixtures within a season or in rotation over seasons? It may be difficult for these businesses to yield short-term profit from turfgrass managers incorporating resistance management practices (both chemical and nonchemical) into weed management programs. However, the process of doing so could extend the useful life of herbicides that are being challenged by herbicide resistance including ALS inhibitors (e.g., foramsulfuron, trifloxysulfuron), mitotic inhibitors (e.g., prodiamine), and glyphosate. Powles and Gaines (2016) proposed a regulatory change granting herbicide registrants extended data exclusivity in exchange for placing use restrictions such as limiting the treatable area (which crops or which geographic areas) or requiring chemistry rotation and/or use only as part of a mixture of MOAs for new herbicides entering the marketplace. When coupled with recent incentives (EPA 2014) for agrochemical companies to register herbicides in minor crops (e.g., turfgrass and ornamentals) in addition to major crops such as corn and soybean, such a regulatory adjustment could have a considerable impact on new herbicide availability for turfgrass systems.

Translation to Turfgrass Managers and Systems

The listening session participants were primarily those, farmers and others, working with agronomic crops. Two of the sessions, one held in the Northeast (Pennsylvania) and the other in California, also had significant representation of vegetable and fruit growers. So, how would any of this apply to those working in turfgrass systems?

Participants at the listening sessions did not want (or think there was a need for) more regulation to deal with resistance. Regulation could take many forms, but one approach might be herbicide label language that requires mixtures of MOAs or specified rotation of MOAs as a way to combat resistance. Caution would have to be exercised with this approach to avoid limiting local adaptations of control practices or conflicts with resistance BMPs. That said, would turfgrass managers be more receptive to these restrictions than those in agronomic crops? Given that turfgrass managers are familiar with the concept of mandatory mixtures and rotation of fungicides for resistance management, they might be more receptive to the same approaches for herbicide resistance management. Moreover, it is well established that even the threat of regulation can change behavior (Ervin et al. 2013).

If diversity in weed management systems is difficult for agronomic crops, it is doubly difficult in turfgrass. The crop is perennial, removing options like tillage and cover crops; there are limited herbicide options, and, in most cases, there are limited cultural controls. There are indications that cultural approaches such as increased mowing height (Cropper et al. 2017; Gannon et al. 2015) can be used to suppress weed species like large crabgrass [*Digitaria sanguinalis* (L.) Scop.], but there is a need for more research in this area. One limitation in many turfgrass situations, such as on golf courses, is that immediate solutions to weed problems are needed, making it unacceptable to wait for cultural control approaches to take effect. However, we should highlight those turfgrass managers who have found ways to diversify their weed management tactics and still meet demands of their clientele.

One area that is ripe for additional research and education for turfgrass is more diverse weed management tactics. What cultural practices can be used in turfgrass that are effective in reducing resistance selection pressure? What information is available to demonstrate the effectiveness of herbicide mixtures and rotations in turfgrass for resistance management? Are there locally adapted templates for proactive resistance management of specific weed species in turfgrass? If turfgrass managers truly believe a new herbicide is not coming to solve their problems, then they are more likely to act proactively to manage resistance. The belief that a new herbicide(s) is coming is a major obstacle to proactive resistance management and more diverse weed management tactics in agronomic crops (Schroeder et al. 2018); this situation may be the case in turfgrass as well, given the rising cost of herbicide discovery.

Although there is certainly a need for expanded research and education regarding herbicide resistance in turfgrass, it is the consensus among the social scientists working with WSSA on this issue that these efforts alone will not solve this "wicked" problem (Ervin and Jussaume 2014). One reason for this is that weeds are mobile. Resistant weeds can move from where they evolve to new locations. Thus, although an individual manager can practice resistance BMPs, the problem is not solved if those surrounding that manager are not doing so. This means the solution requires a community approach. How is community formation promoted? Generally, this is a bottom-up process, not imposed, and can take time. Concern about weeds resistant to multiple herbicides and a connection to university extension programs can help. However, the biggest factor in the formation of communities is the presence and action of champions—locally respected persons concerned enough about the issue to take action and bring others together to tackle the problem.

The HREC, partnering with the Entomological Society of America, has undertaken a project to study the successes and failures of previous community-based efforts to help others design regionally and locally cost-effective cooperative weed management programs. Further, the HREC hopes to develop communication tools to allow sharing of the information gathered. The turfgrass arena would seem ideally structured for the formation of resistance management communities. First, within a state there are already many defined and relatively small communities. There may be turfgrass associations, sports turf associations, golf course superintendent associations, vegetation management associations, and departments of transportation whose members regularly meet and share information. Any and all of these could come together with resistance management strategies that their members could agree to and practice. However, as mentioned above, champions who want to see this happen will be needed for success. The role for extension weed scientists, working with social scientists, will be to encourage and support the champions and the forming communities with both management information and, even more importantly, guidance for the success of the community formation itself.

Conclusion

Although herbicide resistance is an emerging problem in the turfgrass industry, the overall scope of the problem is still small when compared to agronomic cropping systems. Everyone within the turfgrass industry has a responsibility for combating this issue. Herbicide resistance in agronomic cropping systems underscores the challenges that can arise should the problem worsen. There is still time to change the future in turfgrass. The key to this will be the formation of communities catalyzed by champions who are not complacent about the threat of herbicide resistance. These champions and the nascent communities will need support to be successful. Hopefully, a coordinated effort among turfgrass managers, product suppliers, university weed scientists, private consultants, government agencies, national organizations, professional societies, and the press will do just that.

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