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Developing and Implementing a Sustainable, Integrated Weed Management Program for herbicide-resistant Poa annua in turfgrass

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MANAGEMENT GUIDE

Applied Turfgrass Science

Developing and implementing a sustainable, integrated weed management program for herbicide-resistant *Poa annua* in turfgrass

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Abstract

The ability of *Poa annua* L. to adapt to most turfgrass environments extends to its ability to develop resistance to commonly used herbicides. Herbicide resistant *P. annua* is of almost epidemic proportions. The loss of once viable chemical-based treatments pushes practitioners towards more expensive, and often less effective,

Abbreviations:: EPA, Environmental Protection Agency; HRAC, Herbicide Resistance Action Committee; IWM, integrated weed management; MOA, mode of action; SOA, site of action; WSSA, Weed Science Society of America.

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control strategies. This management guide focuses on integrated weed management (IWM) practices for *P. annua* control and herbicide resistance—what it is and how to overcome it. Also discussed are resistance mechanisms and documentation of common occurrences of field-level resistance within much of the United States. Finally, a summary of some of the social and economic constraints that practitioners face in the implementation of IWM strategies for *P. annua* is discussed.

1 | INTRODUCTION

1.1 | Herbicide resistance

Poa annua L. is historically a troublesome, if not important weed of turfgrass (Christians, 1996; Van Wychen, 2020). Reliance upon herbicides as the primary means of control has led to almost overwhelming presence of herbicide resistance globally (Figure 1; Heap, 2023; Norsworthy et al., 2012). There are 49 herbicide resistant *P. annua* cases reported worldwide and there are 18 cases reported in the United States (Heap, 2023). Cases are likely severely under-reported based upon ongoing research (Ignes et al., 2023; Rutland et al., unpublished data, 2023; Singh et al., 2021). The worrying trend is that for some turfgrass scenarios, there are no longer effective means of chemical control (Allen et al., 2022).

Herbicide resistance can have severe economic consequences for turfgrass managers and producers by affecting aesthetics, playability, surface stability, integrity of the desired turfgrass species, and yield (e.g., sod and seed production). To control resistant weeds, turfgrass managers must often increase their input costs by purchasing alternative herbicide chemistries and investing in additional labor to remove resistant weed populations using alternative, integrated weed management (IWM) methods (Carroll et al., 2021a, 2021b; Elmore et al., 2023; Johnson, 1994).

Herbicide resistance occurs from the repeated use of herbicides with the same site of action (SOA), or mechanism, which therefore selects for resistant plants (Norsworthy et al., 2012). These uncontrolled plants reproduce, leading to an increased prevalence of resistance within a local population. Progeny from the resistant population may move off-site as seed on equipment or athletic attire.

Options for controlling resistant populations are improved by understanding what herbicides the resistant population is susceptible to. Ultimately, chemical weed control with multiple SOA will be more effective and long-lived than repeatedly relying on one SOA (Cross et al., 2015). Furthermore, chemical control strategies are only one of several integrated approaches to managing herbicide resistant *P. annua* (Barua et al., 2021; Brosnan et al., 2020; Carroll et al., 2021a, 2021b; Guertal & McElroy, 2018; Imaizumi et al., 1997; Varco & Sartain, 1986).

1.2 | How herbicides work

Herbicides can be classified in various ways, but the intent of any classification system should be to characterize the use in a particular crop or scenario. To quote Zimdahl (2013), "An adequate classification cannot be created for any group as large as herbicides by dividing the group in two." In turfgrass, like many other cropping systems, herbicides are classified foremost as "preemergence" or "postemergence" herbicides. Preemergence, or residual herbicides, prevent successful germination and maturation of seedling weeds but may also negatively affect the intended turfgrass crop through the same mechanism (e.g., inhibition of root or shoot growth). Postemergence herbicides are applied on existing weeds or to established crops. Note that there is considerable crossover between pre- and postemergence herbicides, with a spectrum rather than polar range of activities of many herbicides. Herbicides are generalized as either "selective" or "non-selective." Selectivity is affected by turfgrass species tolerance, weed susceptibility, application rate, and application technology (e.g., liquid- or granular-applied), among others. Furthermore, herbicides can be "contact" or "systemic" in nature. Contact herbicides are generally absorbed through the leaf surface and do not require extensive translocation within the plant to be effective. Contact herbicides may disrupt cell membranes, causing plant cells to rupture and rapidly degrade. Alternatively, systemic herbicides are absorbed by roots and/or foliage and translocate within the plant.

To enter and circulate within a plant, herbicide molecules may move through either the apoplast, symplast, or both (Zimdahl, 2013). The apoplast consists of nonliving parts of a plant where water movement occurs by passive diffusion (i.e., driven by transpiration of water from the roots up through the plant and eventually into the atmosphere). The symplast refers to the continuous arrangement of interconnected living tissue. In this tissue, water movement occurs by osmosis and/or active transport.

A mode of action (MOA) or SOA refers to the process or location within a plant that is affected after foliage, roots, or seeds come into contact with the herbicide. Mode of action describes the broad process within the plant that is disrupted by an herbicide. That MOA involves absorption into the plant, translocation or movement within the plant, metabolism of the herbicide, and the physiological plant response. Site of action and MOA are often used interchangeably to describe the specific physiological binding site or enzymatic process within the plant that is disrupted by an herbicide. Examples of herbicidal activity include build-up of toxic byproducts, decreased light harvesting, and reduced production of components like amino acids or cofactors for other plant processes (Shaner, 2014; Weed Science Society of America, 2021; Zimdahl, 2013).

1.3 | Herbicide site of action classification

In 1995, the Herbicide Resistance Action Committee (HRAC) and Weed Science Society of America (WSSA) commissioned an herbicide categorization system based on herbicide SOA (Retzinger & Mallory-Smith, 1997). A classification system was developed with the idea that if herbicide SOAs were well known, recommendations for herbicide resistance management would be easier to understand. With few exceptions, herbicides with the same SOA are assigned a group number (Figure 2; Weed Science Society of America, 2021). These numbers are commonly listed on herbicide product labels and may also list the active ingredient. The US Environmental Protection Agency (EPA) currently recommends that herbicide labels display the group number that identifies the SOA for all active ingredients in the product (Figure 3). Rotation among herbicide SOAs between years and within seasons is crucial to slowing the evolution of herbicide resistance. However, mixing or using premixtures of effective herbicides with different SOAs may delay resistance longer than single-herbicide applications alone or in annual sequence (Norsworthy et al., 2012).

1.4 | Resistance evolution

After an herbicide application, plants that escape control produce seed and become more widespread in the environment, leading to an increased resistant population in the local seedbank (Norsworthy et al., 2012). That population may move off-site as seed or vegetatively.

Currently, resistance to 21 of the 31 known SOA are reported (515 herbicide resistant weeds [species × SOA] listed worldwide; Heap, 2023). The United States represents roughly 30% of these cases. Globally, weed species are accumulating resistance mechanisms (Gaines et al., 2020), displaying multiple resistance across many herbicides (Powles & Yu, 2010), and are posing a greater challenge to herbicide sustainability in world agriculture (Gould et al., 2018). Mechanisms of resistance are simply how plants can tolerate or recover from an herbicide application. Resistance mechanisms are classified as either target site or nontarget site resistance.

Core Ideas

- *Poa annua* herbicide resistance is common worldwide.
- An integrated weed management (IWM) strategy is necessary to combat herbicide resistance and maximize control.
- Management success relies upon a diverse range of control options and stakeholder cooperation.
- Economics and biological complexity of the problem pose a significant constraint to IWM adoption.

1.4.1 | Target-site resistance

Target site resistance occurs when the intended herbicide binding location undergoes a conformational change in structure. This change reduces the binding of an herbicide at the SOA, thus reducing herbicide efficacy. Most targeted plant populations have very low occurrence of this structural "defect." In fact, the binding sites that are structurally different from that normally present in the natural population may have a negative consequence on the plant's health, referred to as "fitness penalty" or "fitness cost" (Vila-Aiub et al., 2009). The process of repeated selection using the same herbicide SOA expands this trait across an entire population, leading to population-wide resistance. Target site resistance in *P. annua* in the United States is reported to acetolactate synthase (ALS) Inhibitors (Group 2) (Brosnan et al., 2015, 2016; Cross et al., 2013; McElroy et al., 2013; Rutland et al., unpublished data, 2023), microtubule assembly inhibitors (Group 3) Ignes et al., 2023; Rutland et al., 2022; Rutland et al., unpublished data, 2023), photosystem II (PSII) inhibitors (Group 5) (Kelly et al., 1999; Perry et al., 2012; Rutland et al., unpublished data, 2023), and enolpyruvyl shikimate-3-phosphate (EPSP) synthase inhibitors (Group 9) (Rutland et al., unpublished data, 2023). In some cases, the *P. annua* is resistant to more than one SOA (Brosnan et al., 2015; Ignes et al., 2023; Singh et al., 2021).

1.4.2 | Non-target site resistance

Non-target site resistance is associated with the plant's ability to metabolize an herbicide or plant characteristics that decrease herbicide absorption or translocation, which may lead to ineffective control (Gaines et al., 2020). There are

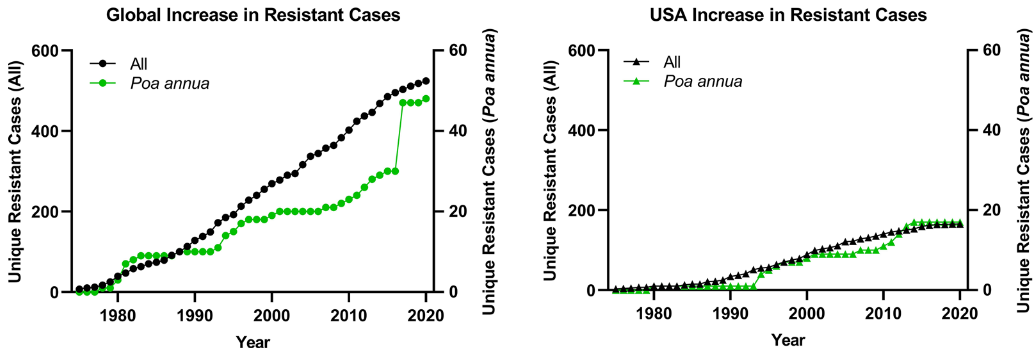

FIGURE 1 Chronological increase in unique resistant weeds (independently observed and reported populations) and *Poa annua* cases globally, and the increase in unique resistant weeds and *P. annua* cases in the United States (Heap, 2023).

many ways non-target site resistance can occur, such as reduced herbicide absorption through plant leaves, reduced translocation, sequestration of herbicide into the vacuoles, or alteration of the activity of transporters present in the plasma membrane.

Metabolism based non-target site resistance may increase activity of metabolic enzymes, such as cytochrome P450 and glutathione *S*-transferase. These enzymes enhance the defense system of plants and may bind the herbicides and render them inert or ineffective. Cases of non-target site resistance in *P. annua* in the United States are currently few and include a report on atrazine (Group 5) (Svyantek et al., 2016) and also methiozolin (WSSA Group 30) (Brosnan et al., 2016). The mechanism of resistance in *P. annua* to other herbicides, such as ethofumesate (Group 15) and indaziflam (Group 29), is currently unknown. Overall, there are many ongoing research projects on the topic of herbicide resistance mechanisms in *P. annua*, and future discoveries in this area will be beneficial in developing control strategies.

2 | SCREENING

2.1 | Screening for resistance

Confirming resistance in weed species such as *P. annua* requires use of scientific protocols; simply failing to be controlled by a single herbicide treatment in the field does not result in a plant being designated as "resistant" (Beckie et al., 2000; Heap, 2005). To be defined as a resistant weed, the plant in question must survive a dose of herbicide that is normally lethal to the wild type; the response must be heritable and must be confirmed using a scientific protocol. Furthermore, the response must have practical field impact, and the species must be naturally occurring in the field.

Scientific protocols to confirm resistance have been reviewed (Burgos et al., 2013) and are updated as both technology (to conduct research on resistance) and new cases of herbicide resistance evolve or are reported. Classically, resistance confirmation is conducted via dose-response experiments where putative resistant plants are exposed to a wide range of herbicide doses under controlled conditions, along with a biotype (of the same species) known to be herbicide susceptible. A quantifiable response variable (e.g., biomass) is used to compare the presumed-resistant and susceptible biotypes across the range of doses studied. While effective, this method is time consuming and limits the ability to return results to practitioners within the season.

Efforts have been made to develop laboratory bioassays to screen suspect weeds for herbicide resistance more expeditiously (Burgos et al., 2013). These tests, often called "quick tests" or "rapid assays" are conducted in tissue culture media and are advantageous because they can be used to discern resistance, whether the mechanism is a function of target site mutation, metabolism, sequestration, or altered biokinetics (Gaines et al., 2020; Kaundun, 2021). Similar to classical dose response tests, rapid assays require known susceptible and resistant plant material for the herbicide in question. Given that herbicides are typically more bioavailable in tissue culture media (compared to soil), herbicide doses used in these assays may not be easily transferable to field conditions.

In *P. annua*, assays using tissue culture agar have been developed to discern resistance to active ingredients within the following herbicide groups:

- Group 2 – trifloxysulfuron (Brosnan et al., 2017; Cross et al., 2013)
- Group 3 – prodiamine, pendimethalin, dithiopyr (Cutulle et al., 2009)
- Group 5 – simazine (Kelly et al., 1999)
- Group 9 – glyphosate (Brosnan et al., 2017)
- Group 29 – indaziflam (Pritchard, 2022)

While these assays can be used by laboratories to return results to turfgrass managers in ≤14 days (once seed is available), they only explore *P. annua* response to a limited cohort of herbicides used for control in the field. In situations where a rapid test is not available, classical dose-response testing (using whole plants) is the preferred method of resistance testing. For herbicides that are primarily absorbed via foliage

FIGURE 2 This Herbicide Classification Poster categorizes herbicides that are commonly used to control *Poa annua* in turfgrass systems. Categories are based upon unique binding sites and mechanism of binding within a plant. This poster is free to download at: resistpoa.org/tools/site-of-action-poster/

FIGURE 3 An example of the first page of an herbicide label showing the Herbicide Resistance Action Committee (HRAC) / Weed Science Society of America (WSSA) Group 2 (acetolactate-synthase inhibiting herbicides), clearly visible at the top of the label. This communicates to users the active ingredient and the site of action for the product.

(e.g., glufosinate-ammonium), this can be conducted using mature plants established in peat-based greenhouse growing media, whereas those absorbed via plant roots (e.g., pronamide) should be tested using soil similar to that present at the field site from which plants are collected.

2.2 | Resist *Poa*: An example of herbicide resistance screening

Individual turfgrass sectors (golf courses, athletic fields, sod production, and lawn care operations) each perform unique management practices related to turfgrass selection, mowing, irrigation, cultivation, and labeled pesticide use. In many cases, soils may also be significantly modified to support a particular use. For example, many golf greens, tee boxes, and professionally managed athletic fields may have a constructed sand-based rootzone to support infiltration and traffic tolerance.

Many of these practices and characteristics that make a turfgrass sector unique can play an important role in a site's susceptibility to herbicide resistance. This can be due in part to the way in which particular management practices (e.g., irrigation, fertilization, mowing) affect the turfgrass's ability to be competitive, allowing *P. annua* populations to thrive. Susceptibility to resistance may also be due to the limited number of herbicides labeled for particular use sites. For example, some herbicides are labeled for postemergence control of *P. annua* on golf course putting greens. Similarly, some products may not be suitable for a particular turfgrass species or soil type. Further, some herbicides diminish in activity in certain soil types (Brosnan et al., 2013). These limitations can impact a turfgrass manager's ability to rotate SOA in their program, making it all the more important to develop a strong IWM program.

A team of 16 university scientists in the United States have collected almost 1,400 unique populations of *P. annua* across 23 states (Rutland et al., unpublished data, 2023). In an effort to collect as much information as possible about herbicide resistance in US *P. annua* populations, scientists sought to collect populations across five unique USDA hardiness zones (5 through 9) and four turfgrass industry sectors (golf courses, athletic fields, sod production, and lawn care operations) (Figure 4).

To date, 1349 of these populations have been screened for herbicide resistance with at least 568 populations suspected of resistance to one or more herbicide SOA following a 1× rate screening (Figure 5) (Rutland et al., unpublished data, 2023). It is important to note that this initial screening methodology does not "confirm" resistance but only identifies "suspected" resistance. Additional experiments are conducted with each population "suspected" of resistance to both "confirm" and "quantify" the level of resistance as well as to identify the mechanism of resistance.

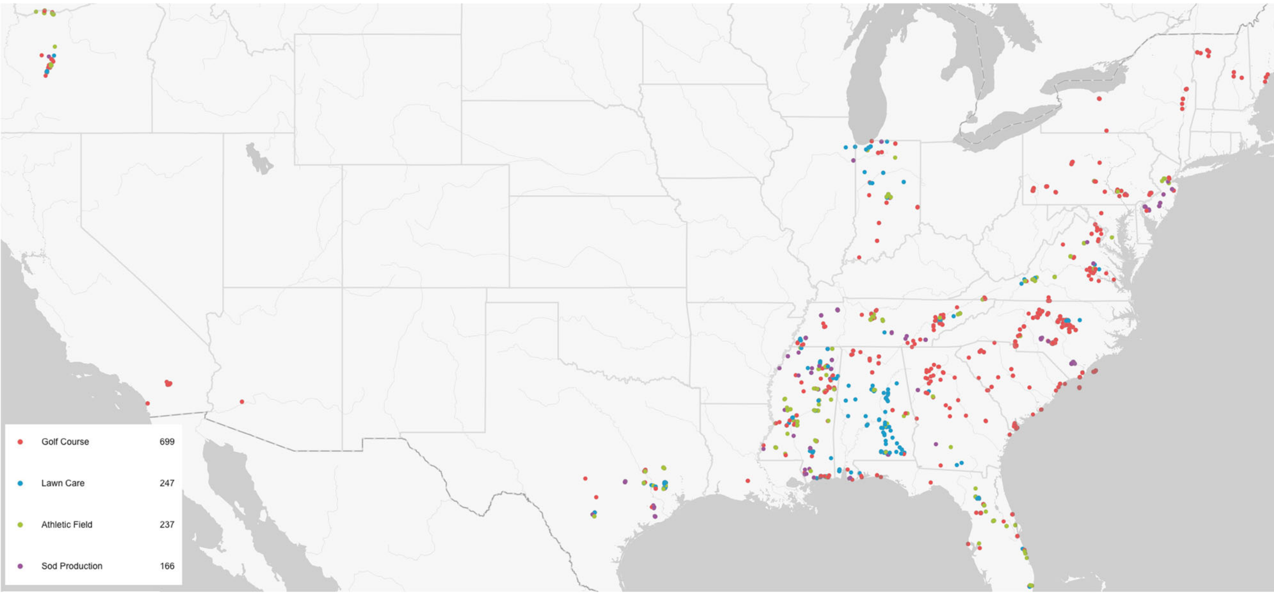

FIGURE 4 Sampling locations for 1349 total screened *Poa annua* populations across four turfgrass systems: golf courses ($n = 699$), lawn care ($n = 247$), athletic fields ($n = 237$), and sod production ($n = 166$).

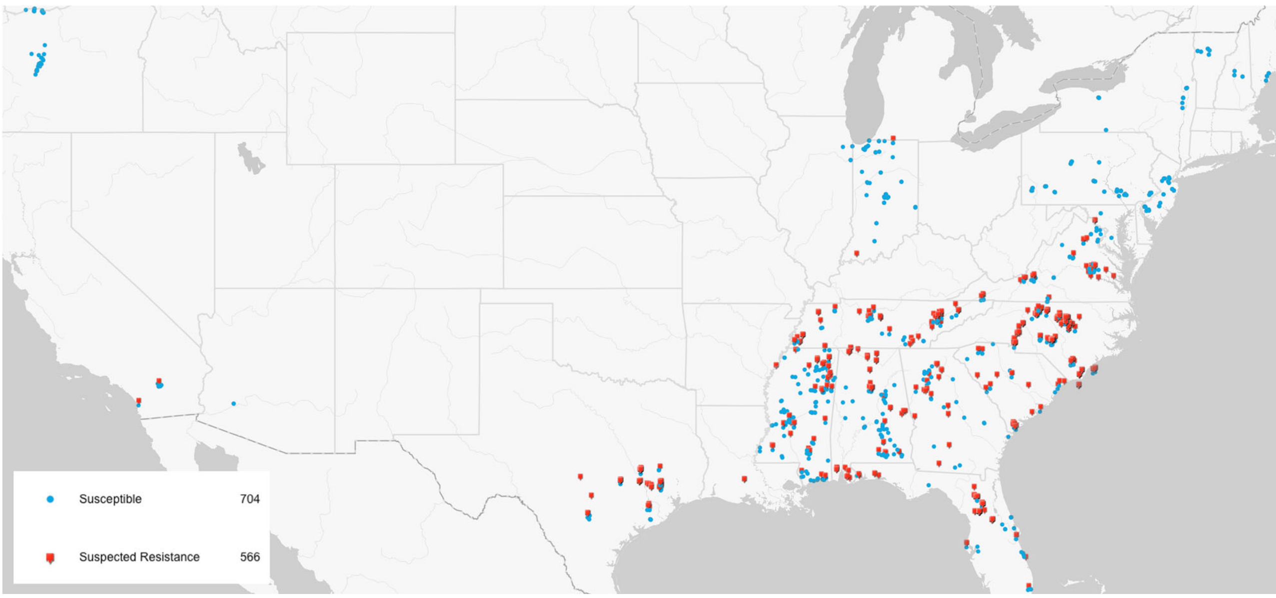

FIGURE 5 Distribution of herbicide-susceptible ($n = 781$) *Poa annua* populations and populations with suspected herbicide-resistance ($n = 568$) to one or more herbicides following a 1× label rate screening.

3 | INTEGRATED WEED MANAGEMENT

3.1 | Developing an effective/sustainable management program

Herbicide resistance is often present before it is prevalent or detectable. A successful control strategy relies upon practices that reduce *P. annua* density, thereby reducing the probability for resistant biotypes. When suspected, diagnosing herbicide resistance is possible for most herbicide SOA; although, diagnosis is not always rapid. Understanding alternative herbicide SOA is critical to rotating away from failed options. Table 1 presents common herbicide SOA, use sites, and turfgrass species tolerances for herbicides labeled for *P. annua* control. Table 1 can be used by practitioners to assess what chemical control options are available for their scenario. Any potential

TABLE 1 Preemergence and postemergence herbicide efficacy on *Poa annua*, safety on common cool-season and warm-season grasses, and sites/scenarios where these herbicides are labelled for use.

	WSSA	Control		Cool-season						Warm-season								Site use					
Herbicide (Example trade name)	Site of action	Preemergence	Postemergence	Colonial bentgrass	Creeping bentgrass	Fine fescue	Kentucky bluegrass	Perennial ryegrass	Tall fescue	Bahiagrass	Bermudagrass	Buffalograss	Centipedegrass	Kikuyugrass	Seashore paspalum	St. Augustinegrass	Zoysiagrass	Residential lawn	Commercial lawn	Golf course	Sports fields	Sod farm	Unimproved turf
amicarbazone (Xonerate 2SC)	5[a]	–	F	NR	S	S	S	S	S	S	S	S	S	S	S	S	S	✓	✓	✓	✓	✓	✓
atrazine (AAtrex)	5	E	E	NR	NR	NR	NR	NR	NR	NR	S-I	NR	S	NR	NR	S	S-I	✓	✓	✓	✓	✓	✓
benefin (Balan)	3	G	–	NR	S	S	S	S	S	S	S	S	S	NR	NR	S	S	✓	✓	✓	✓	✓	✓
benefin + oryzalin (Surflan XL)	3	G	–	NR	NR	NR	NR	NR	S-I	S	S	S	S	NR	NR	S	S	✓	✓	✓	✓		✓
benefin + trifluralin (Team Pro)	3	G	–	NR	S	S	S	S	S	S	S	S	S	NR	NR	S	S	✓	✓	✓	✓		✓
bensulide (Bensumec)	0	F	–	S	S	S	S	S	S	S	S	S	S	NR	NR	S	S	✓		✓			
bensulide + oxadiazon (Goosegrass/Crabgrass)	0+14	G	–	NR	S	NR	S	S	S	NR	S	NR	NR	NR	NR	NR	S			✓			
DCPA (Dacthal F)	3	F	–	NR	S	S	S	S	S	S	S	S	S	S	S	S	S		✓	✓	✓	✓	✓
s-dimethenamid (Tower)	15	F	–	NR	S[b]	S[b]	S[cb]	S[b]	S[b]	S	S	S	S	S	S	S	S	✓[b]	✓[b]	✓	✓[b]	✓[b]	✓[b]
s-dimethenamid + pendimethalin (FreeHand)	15+3	G	–	NR	NR	NR	NR	NR	NR	NR	S	S	S	S	S	S	S	✓	✓	✓	✓	✓	✓
diquat (Reward)	22	–	F	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	✓	✓	✓	✓		✓
dithiopyr (Dimension)	3	G	–	NR	S[c]	S[c]	S	S	S	S	S	S	S	S	S	S	S	✓	✓	✓	✓	✓	✓
dithiopyr + isoxaben (Crew)	3+29	G	–	NR	S	S	S	S	S	S	S	S	S	S	S	S	S	✓	✓	✓	✓	✓[d]	✓
ethofumesate (Prograss)	15	G	G	NR	S[c]	NR	S[c]	S	S	NR	RD	NR	NR	NR	NR	S	NR	✓	✓	✓	✓	✓	
flazasulfuron (Katana)	2	–	G	NR	NR	NR	NR	NR	NR	NR	S	S	S	NR	NR	NR	S		✓	✓	✓	✓	✓
flumioxazin (SureGuard)	14	E	E	NR	NR	NR	NR	NR	NR	NR	RD	NR	NR	NR	NR	NR	NR	✓	✓	✓	✓	✓	✓
foramsulfuron (Revolver)	2	–	E	NR	NR	NR	NR	NR	NR	NR	S	S	NR	NR	NR	NR	S	✓	✓	✓	✓	✓	✓
glufosinate (Finale XL T&O)	10	–	F	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	✓	✓	✓	✓	✓	✓
glyphosate (Roundup)	9	–	E	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	✓	✓	✓	✓	✓	✓
glyphosate + 2,4-D (Campaign)	9+4		E	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	✓	✓	✓	✓	✓	✓
glyphosate + diquat (QuikPro)	9+22	–	E	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	RD	✓	✓	✓	✓		✓

(Continues)

TABLE 1 (Continued)

Herbicide (Example trade name)	WSSA	Control		Cool-season						Warm-season								Site use					
	Site of action	Preeme-rgence	Posteme-rgence	Colonial bentgrass	Creeping bentgrass	Fine fescue	Kentucky bluegrass	Perennial ryegrass	Tall fescue	Bahia-grass	Bermud-agrass	Buffa-lograss	Centiped-egrass	Kikuyu-grass	Seashore paspalum	St. Augustine-grass	Zoysi-agrass	Residential lawn	Commercial lawn	Golf course	Sports fields	Sod farm	Unimproved turf
glyphosate + prodiamine (ProDeuce)	9+3	E	E	NR	NR	NR	NR	NR	NR	RD	RD	RD	RD	RD	RD	RD	RD			✓	✓		✓
imazaquin (Image 70DG)	2	–	F	NR	NR	NR	NR	NR	NR	NR	S	NR	S	NR	S	S	S	✓	✓	✓	✓	✓	✓
indaziflam (Specticle FLO or G)	29	E	P	NR	NR	NR	NR	NR	NR	S	S	S	S	NR	NR	S	S	✓	✓	✓	✓	✓	✓
indaziflam + glyphosate + diquat (Specticle Total)	29+9 +22	E	E	NR	NR	NR	NR	NR	NR	RD	RD	RD	RD	NR	NR	RD	RD	✓	✓	✓	✓	✓	✓
mesotrione (Tenacity)	27	P	F	NR	NR	S	S	S	S	NR	RD	S	S	NR	NR	S[e]	NR	✓	✓	✓	✓	✓	✓
methiozolin (PoaCure)	30	E	E	NR	S	S	S	S	S	NR	S	NR	NR	S	S	NR	S			✓			
s-metolachlor (Pennant MAGNUM)	15	G	–	NR	NR	NR	NR	NR	NR	S	S	NR	S	NR	NR	S[e]	S	✓	✓	✓	✓	✓	✓
metribuzin (Sencor)	5	E	G	NR	NR	NR	NR	NR	NR	NR	S	NR	NR	NR	NR	NR	NR	✓	✓	✓	✓		✓
metsulfuron + rimsulfuron (Negate 37WG)	2	P	G	NR	NR	NR	NR	NR	NR	NR	S	NR	NR	NR	NR	NR	S		✓	✓	✓	✓	✓
oryzalin (Surflan)	3	E	–	NR	NR	NR	NR	NR	S-I	S	S	S	S	NR	NR	S	S	✓	✓	✓	✓	✓	✓
oxadiazon (Ronstar G, Ronstar FLO)	14	G	–	NR	S[f]	S[f]	S[f]	S[f]	S[f]	NR	RD	S[f]	NR	NR	NR	RD	RD	✓	✓	✓	✓	✓	✓
oxadiazon + pendimethalin (Jewel, Kansel)	14+3	G	–	NR	NR	NR	S	S	S	NR	S	S	NR	NR	NR	S	S		✓	✓	✓		✓
oxadiazon + prodiamine (Regalstar G)	14+3	G	–	NR	S[f]	S[f]	S[f]	S[f]	S[f]	NR	S[f]	S[f]	NR	NR	NR	NR	S[f]		✓	✓	✓		✓
pendimethalin (Pendulum)	3	G	–	NR	S[g]	S	S	S	S	S	S	S	S	NR	S	S	S	✓	✓	✓	✓	✓	✓
prodiamine (Barricade)	3	G	–	NR	S	S	S	S	S	S	S	S	S	S	S	S	S	✓	✓	✓	✓	✓	✓

(Continues)

TABLE 1 (Continued)

Herbicide (Example trade name)	WSSA	Control		Cool-season						Warm-season								Site use					
	Site of action	Preeme-rgence	Posteme-rgence	Colonial bentgrass	Creeping bentgrass	Fine fescue	Kentucky bluegrass	Perennial ryegrass	Tall fescue	Bahia-grass	Bermud-agrass	Buffa-lograss	Centiped-egrass	Kikuyu-grass	Seashore paspalum	St. Augustine-grass	Zoysi-agrass	Residential lawn	Commercial lawn	Golf course	Sports fields	Sod farm	Unimproved turf
prodiamine + isoxaben (Gemini)	3+29	G	–	NR	S	S	S	S	S	S	S	S	S	S	S	S	S	✓	✓	✓	✓	✓	✓
prodiamine + quinclorac (Cavalcade PQ)	3+4	G	–	NR	S-I	S-I	S	S	S	NR	S	S	NR	NR	S	NR	S	✓	✓	✓	✓	✓	✓
prodiamine + sulfentrazone (Echelon)	3+14	G	–	NR	S	S[c]	S	S	S[c]	S	S	S	S	S	S	NR	S	✓	✓	✓	✓	✓	✓
pronamide (Kerb SC T&O)	3	E	G	NR	NR	NR	NR	NR	NR	NR	S	S	S	NR	NR	S	S		✓	✓	✓	✓	✓
rimsulfuron (Rimsulfuron 25DF)	2		E	NR	NR	NR	NR	NR	NR	NR	S	S	S	NR	NR	NR	S	✓	✓	✓	✓	✓	✓
simazine (Princep)	5	E	G	NR	NR	NR	NR	NR	NR	NR	S-I	S	S	NR	NR	S	S-I	✓	✓	✓	✓	✓	✓
simazine + prodiamine + imazaquin (Coastal)	5+3+2	E	G	NR	NR	NR	NR	NR	NR	NR	S-I	NR	S	NR	NR	S	S-I	✓	✓	✓	✓	✓	✓
sulfosulfuron (Certainty)	2	–	G	NR	NR[h]	NR	NR[h]	NR	NR	S	S	S	S	S	S	S	S	✓	✓	✓	✓	✓	✓
thiencarbazone + foramsulfuron + halosulfuron (Tribute TOTAL)	2	–	E	NR	NR	NR	NR	NR	NR	NR	S	NR	NR	NR	NR	NR	S	✓	✓	✓	✓	✓	✓
trifloxysulfuron (Monument)	2	–	E	NR	NR	NR	NR	NR	NR	NR	S	S-I	NR	NR	NR	S[e]	S	✓	✓	✓	✓	✓	✓

Rating Key: E = excellent (≥90% control). G = good (75-90% control). F = fair (50-75% control). P = poor control (≤50% control). A dash (-) indicates that no control is expected from the herbicide at the indicated timing. S = safe at labeled rates on healthy, mature turfgrass. I = intermediate safety or some injury may occur, may cause minor damage to mature, healthy turfgrass. Consider using the lower end of the rate range. Do not apply to turfgrasses under stress. RD = a non-selective herbicide for renovation (R) or weed control in dormant (D) warm-season grasses. NR = not registered for use on this species. Data in tables is based on label guidance and research conducted at U.S. land-grant institutions (Patton et al., 2022).

[a]The Weed Science Society of America (WSSA) developed a classification system to identify the biochemical site where an herbicide works to kill a weed. The WSSA system uses a numerical code (group number), which is located at the top of the herbicide label. For each herbicide, the number is a descriptive code for the mechanism of action (MOA). Utilizing sound cultural practices to enhance turfgrass growth, rotating herbicide site of action, and applying herbicide mixtures are best practices to prevent herbicide resistance.

[b]For use on cool- and warm-season grasses on golf courses (see label), and warm-season use only on sod farms, commercial and recreational turf, and residential turfgrass.

[c]Safety varies by cultivar.

[d]Cannot be used for turfgrass renovation on sod farms but may be used for weed control in dormant, established turfgrass.

[e]Sod farms only.

[f]Ronstar G and Oxadiazon 2G are the only oxadiazon formulations registered for use on cool-season turfgrass and buffalograss. Apply to dry foliage and water-in with irrigation immediately after application to reduce potential for turfgrass injury.

[g]Pendulum 3.3EC and other 3.3EC formulations of pendimethalin are not labeled for use on creeping bentgrass.

[h]A label change in May 2011 no longer allows for the use of Certainty turfgrass herbicide on cool-season turfgrass. Product packaged before these changes can continue to be used according to label directions in cool-season turfgrass. Previous label stipulations recommended that Certainty was safe for use on creeping bentgrass, 100% Kentucky bluegrass turf, or for use on Kentucky bluegrass + perennial ryegrass and/or fine fescue mixtures, but not safe for use on tall fescue + Kentucky bluegrass mixtures.

resistance issues on-site should be diagnosed, and herbicides should be chosen in lieu of this information.

No single practice or strategy will completely eliminate *P. annua* from turf. Integrated weed management techniques require a balance of both chemical and non-chemical tactics used in conjunction with one another (Elmore et al., 2023):

- It is necessary to decrease reliance upon chemical weed control and increase diversity of traditional cultural practices, such as selection of appropriate turfgrass species and variety for the scenario or environment. The emphasis should be on providing a dense and competitive turfgrass sward. A holistic approach of managing soil and plant health is required to do so (Elmore et al., 2023).
- When herbicides are used, diversify SOA between years and within seasons (Norsworthy et al., 2012).
- Emphasis should be on *both* preemergence followed by early postemergence means of control (Patton et al., 2018), which may reduce the amount of *P. annua* exposed to postemergence-alone strategies.
- Use labeled rates at appropriate timings and stages of growth (Norsworthy et al., 2012).
- Use multiple herbicide SOA in spray mixes with overlapping spectrums of weeds controlled (Norsworthy et al., 2012).
- Scout after application and avoid allowing weeds to go to seed or proliferate vegetatively (Norsworthy et al., 2012).

Non-chemical approaches should be implemented first and followed by effective herbicide programs where needed. No single program can stand alone. Programs need to be customized for each location based on their resistance issues, turfgrass species, soil type, labor and materials budget, and type of use site. Further, programs will change over time as products leave and enter the marketplace; as site uses, budgets, or expectations change; or as resistance evolves.

3.2 | Overcoming social and economic constraints

Turfgrass managers face several social and economic constraints that hinder the use of IWM strategies. While financial viability is a key constraint, other social and economic factors may also influence weed control decisions. The long-term net benefit of reducing herbicide resistant weeds depends on a host of factors, including local environment, community effects, and rapidly developing weed management technologies, yet an IWM approach requires short-term adaptive planning that practitioners may be reluctant to incur. Focus group discussions with turfgrass professionals reveal that many practitioners hope for new chemical discoveries to better control *P. annua* but feel that government policies are delaying the discovery and implementation of new chemicals (Allen et al., 2022; Ervin et al., 2022).

3.3 | Coordination and leadership as catalysts for IWM adoption

The potential for weed movement across property boundaries suggests that coordination among turfgrass managers may achieve more efficient control (Ervin & Frisvold, 2016). One example of where cooperation achieved sustainable pest control was the control of the cotton boll weevil (*Anthonomus grandis* Boheman) in southeastern states and the pink bollworm (*Pectinophora gossypiella* Saunders) in southwestern states (Shaw et al., 2020). However, this potentially complicates management responses by requiring cooperation regarding the practices that each operator must implement. One bioeconomic model evaluating the effects of implementing resistance management strategies in some cropping systems found that cumulative benefits often exceeded cumulative costs in as little as 2 to 3 years, particularly when there was coordination among neighbors (Livingston et al., 2016).

Individual champions can bolster cooperative efforts, though studies of the roles of such champions to foster IWM are rare. Dentzman et al. (2020) discuss the importance of local leaders in facilitating community-based efforts to promote cooperative pest management in Iowa's promotion of IWM. Another study discusses the efforts of a University of Arkansas Extension Specialist in the early success of the Zero Tolerance program to control palmer amaranth (*Amaranthus palmeri* S. Wats.) in Clay County, Arkansas (Barber et al., 2014). These studies demonstrate that the identification of such trusted leaders will be an important task in fostering cooperation and the advancement of IWM in the turfgrass industry.

3.4 | Credible, accessible, and consistent information sharing

The absence of reliable information sources on IWM practices for turfgrass managers poses a significant constraint to adoption. The search and transaction costs for implementing IWM are difficult to quantify and are often not included in economic evaluations. For those without responsive and credible information networks, the search costs, especially management time requirements, may be too burdensome to pursue.

In the case of agronomic systems, the need for more consistent education of farmers and stakeholders in agriculture about herbicide resistance and management approaches serves as a key lesson (Schroeder et al., 2018). Study participants identify the need for more communication and collaboration among different government levels (e.g., federal, state, and local) with farmers, non-farm groups, universities, and private-sector firms. Participants desire consistent messaging about effective herbicide resistance control options, (e.g., rotating modes of action) to avoid confusion about the best approach for their situations. Similar priorities may benefit the advancement of IWM in turfgrass systems by facilitating easy access to credible and consistent information for implementation.

4 | CONCLUSIONS

The management of *P. annua* herbicide resistance is a serious problem with no standard solution across regions or even within specific regions (Jussaume & Ervin, 2016). Currently, researchers are developing decision support tools to aid in the development of solutions. Practitioners are encouraged to visit http://resistpoa.org/ to learn more. Increased knowledge of the biology and non-chemical control of *P. annua* coupled with increased knowledge of herbicide resistance is needed to take steps to combat the problem. While eradication of herbicide resistance in *P. annua* is not feasible, coordination, research, and education will hopefully allow for the advancement of IWM and improved weed control in turfgrass systems.

AUTHOR CONTRIBUTIONS

James D. McCurdy: Conceptualization; investigation; methodology; project administration; supervision; writing—original draft preparation; writing—review and editing. **Rebecca G. Bowling**: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; supervision; visualization; writing—original draft preparation; writing—review and editing. **Edicarlos B. de Castro**: Investigation; writing—original draft preparation; writing—review and editing. **Aaron J. Patton**: Investigation; methodology; supervision; visualization; writing—original draft preparation; writing—review and editing. **Alec R. Kowalewski**: Investigation; supervision; writing—review and editing. **Clint M. Mattox**: Investigation; writing—review and editing. **James T. Brosnan**: Investigation; supervision; writing—review and editing. **David E. Ervin**: writing—review and editing. **Shawn D. Askew**: Investigation; supervision; writing—review and editing. **Clebson G. Goncalves**: Investigation; writing—review and editing. **Matthew T. Elmore**: Investigation; supervision; writing—review and editing. **J. Scott McElroy**: Investigation; supervision; writing—review and editing. **Brandon C. McNally**: Investigation; writing—review and editing. **Benjamin D. Pritchard**: Investigation; writing—review and editing. **John E. Kaminski**: Investigation; supervision; writing—review and editing. **Muthukumar V. Bagavathiannan**: Funding acquisition; project administration; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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REFERENCES

Allen, J. H., Ervin, D. E., Frisvold, G. B., Brosnan, J. T., McCurdy, J. D., Bowling, R. G., Patton, A. J., Elmore, M. T., Gannon, T. W., McCarty, L. B., Mccullough, P. E., Kaminski, J. E., Askew, S. D., Kowalewski, A. R., Unruh, J. B., McElroy, J. S., & Bagavathiannan, M. V. (2022). Herbicide-resistance in turf systems: Insights and options for managing complexity. *Sustainability*, *14*, 13399. https://doi.org/10.3390/su142013399

Barber, L. T., Smith, K. L., Scott, R. C., Norsworthy, J. K., & Vangilder, A. M. (2014). *Zero tolerance: A community-based program for glyphosate resistant palmer amaranth management* (University of Arkansas Cooperative Extension Services Publication no. FSA2177). University of Arkansas.

Barua, R., Boutsalis, P., Kleemann, S., Malone, J., Gill, G., & Preston, C. (2021). Alternative herbicides for controlling herbicide-resistant annual bluegrass (*Poa annua* L.) in turf. *Agronomy 2021*, *11*, 2148.

Beckie, H. J., Heap, I. M., Smeda, R. J., & Hall, L. M. (2000). Screening for herbicide resistance in weeds. *Weed technology*, *14*(2), 428–445. https://doi.org/10.1614/0890-037X(2000)014%5b0428:SFHRIW%5d2.0.CO;2

Brosnan, J. T., Breeden, G. K., Vargas, J. J., & Grier, L. (2015). A biotype of annual bluegrass (*Poa annua*) in Tennessee is resistant to inhibitors of ALS and photosystem II. *Weed Science*, *63*(1), 321–328. https://doi.org/10.1614/WS-D-14-00080.1

Brosnan, J. T., Breeden, G. K., Zobel, J. M., Patton, A. J., & Law, Q. D. (2020). Nonchemical annual bluegrass (*Poa annua*) management in zoysiagrass via fraise mowing. *Weed Technology*, *34*(4), 482–488. https://doi.org/10.1017/wet.2019.136

Brosnan, J. T., Calvache, S., Breeden, G. K., & Sorochan, J. C. (2013). Rooting depth, soil type, and application rate effects on creeping bentgrass injury with amicarbazone and methiozolin. *Crop Science*, *53*(2), 655–659. https://doi.org/10.2135/cropsci2012.07.0414

Brosnan, J. T., Vargas, J. J., Breeden, G. K., Grier, L., Aponte, R. A., Tresch, S., & Laforest, M. (2016). A new amino acid substitution (Ala-205-Phe) in acetolactate synthase (ALS) confers broad spectrum resistance to ALS-inhibiting herbicides. *Planta*, *243*(1), 149–159. https://doi.org/10.1007/s00425-015-2399-9

Brosnan, J. T., Vargas, J. J., Reasor, E. H., Viggiani, R., Breeden, G. K., & Zobel, J. M. (2017). A diagnostic assay to detect herbicide resistance in annual bluegrass (*Poa annua*). *Weed Technology*, *31*(4), 609–616. https://doi.org/10.1017/wet.2017.26

Burgos, N. R., Tranel, P. J., Streibig, J. C., Davis, V. M., Shaner, D., Norsworthy, J. K., & Ritz, C. (2013). Confirmation of resistance to herbicides and evaluation of resistance levels. *Weed Science*, *61*(1), 4–20. https://doi.org/10.1614/WS-D-12-00032.1

Carroll, D. E., Brosnan, J. T., McCurdy, J. D., De Castro, E. B., Patton, A. J., Liu, W., Kaminski, J. E., Tang, K., McCullough, P. E., & Westbury, D. (2021a). Germinability of annual bluegrass seed during spring in the Eastern United States. *Crop, Forage & Turfgrass Management*, *7*(2), e20117.

Carroll, D. E., Brosnan, J. T., Unruh, J. B., Stephens, C. A., Mckeithen, C., & Boeri, P. A. (2021b). Non-chemical control of annual bluegrass (*Poa annua*) in bermudagrass (*Cynodon* spp.) via fraise mowing: Efficacy and barriers to adoption. *Sustainability*, *13*(15), 8124. https://doi.org/10.3390/su13158124

Christians, N. (1996). A historical perspective of annual bluegrass control. *Golf Course Management*, *64*(11), 49–57.

Cross, R. B., Bridges, W. C., Mccarty, L. B., & McElroy, J. S (2015). Evaluating annual bluegrass herbicide resistance evolution in golf course fairways. *Weed Technology*, *29*(3), 488–500. https://doi.org/10.1614/WT-D-14-00151.1

Cross, R. B., Mccarty, L. B., Tharayil, N., Whitwell, T., & Bridges, W. C. (2013). Detecting annual bluegrass (*Poa annua*) resistance to ALS-inhibiting herbicides using a rapid diagnostic assay. *Weed Science*, *61*(3), 384–389. https://doi.org/10.1614/WS-D-12-00172.1

Cutulle, M. A., McElroy, J. S., Millwood, R. W., Sorochan, J. C., & Stewart, C. N (2009). Selection of bioassay method influences detection of annual bluegrass resistance to mitotic-inhibiting herbicides. *Crop Science*, *49*(3), 1088–1095. https://doi.org/10.2135/cropsci2008.05.0242

Dentzman, K., Pilcher, C., Bagavathiannan, M., Barrett, M., & Burke, I. (2020). Lessons in building community capacity for managing agricultural pests: A science policy experience in Iowa. *Outlooks on Pest Management*, *31*(6), 249–256. https://doi.org/10.1564/v31_dec_02

Elmore, M. T., Patton, A. J., Gannon, T. W., & Brosnan, J. T. (2023). Advances in turfgrass weed management. In M. Fidanza (Ed.), *Achieving Sustainable Turfgrass Management*. Burleigh Dodds Science Publishing.

Ervin, D. E., Dixon, L. M., Montry, A., Patton, A. J., Bowling, B., Elmore, M. T., Gannon, T. W., Kaminski, J. E., Kowalewski, A. R., McCurdy, J. D., McElroy, J. S., Unruh, J. B., & Bagavathiannan, M. V. (2022). Contemporary challenges and opportunities for improved lawn weed management: Insights from U.S. lawn care operations. *Outlooks on Pest Management*, *33*(3), 95–100. https://doi.org/10.1564/v33_jun_04

Ervin, D. E., & Frisvold, G. B. (2016). Community-based approaches to herbicide-resistant weed management: Lessons from science and practice. *Weed Science*, *64*(S1), 609–626. https://doi.org/10.1614/WS-D-15-00122.1

Gaines, T. A., Duke, S. O., Morran, S., Rigon, C. A. G., Tranel, P. J., Küpper, A., & Dayan, F. E. (2020). Mechanisms of evolved herbicide resistance. *Journal of Biological Chemistry*, *295*(30), 10307–10330. https://doi.org/10.1074/jbc.REV120.013572

Gould, F., Brown, Z. S., & Kuzma, J. (2018). Wicked evolution: Can we address the sociobiological dilemma of pesticide resistance? *Science*, *360*(6390), 728–732. https://doi.org/10.1126/science.aar3780

Guertal, E. A., & McElroy, J. S. (2018). Soil type and phosphorus fertilization affect *Poa annua* growth and seedhead production. *Agronomy Journal*, *110*, 2165–2170. https://doi.org/10.2134/agronj2018.02.0139

Heap, I. (2005). Criteria for confirmation of herbicide-resistant weeds. Herbicide Resistance Action Committee. https://hracglobal.com/files/Criteria-for-Confirmation-of-Herbicide-Resistant-Weeds.pdf

Heap, I. (2023). *The international herbicide-resistant weed database*. WeedScience. www.weedscience.org

Ignes, M., McCurdy, J. D., McElroy, J. S., de Castro, E. B., Ferguson, J. C., Meredith, A. N., Rutland, C. A., Stewart, B. R., & Tseng, T. P. (2023). Target and non-target site mechanisms of pronamide resistance in annual bluegrass (*Poa annua*) populations from Mississippi golf courses. *Weed Science*, in press. https://doi.org/10.1017/wsc.2023.17

Imaizumi, S., Nishino, T., Miyabe, K., Fujimori, T., & Yamada, M. (1997). Biological Control of Annual Bluegrass (*Poa annua* L.) with a Japanese Isolate of Xanthomonas campestrispv. poae (JT-P482). *Biological Control*, *8*(1), 7–14. https://doi.org/10.1006/bcon.1996.0475

Johnson, B. J (1994). Biological control of annual bluegrass with *Xanthomonas campestris* pv. poannua in bermudagrass. *Hortscience*, *29*(6), 659–662. https://doi.org/10.21273/HORTSCI.29.6.659

Jussaume, R. A., & Ervin, D. (2016). Understanding weed resistance as a wicked problem to improve weed management decisions. *Weed Science*, *64*(S1), 559–569. https://doi.org/10.1614/WS-D-15-00131.1

Kaundun, S. S. (2021). Syngenta's contribution to herbicide resistance research and management. *Pest Management Science*, *77*(4), 1564–1571. https://doi.org/10.1002/ps.6072

Kelly, S. T., Coats, G. E., & Luthe, D. S. (1999). Mode of resistance of triazine-resistant annual bluegrass (*Poa annua*). *Weed Technology*, *13*(4), 747–752. https://doi.org/10.1017/S0890037x00042172

Livingston, M., Fernandez-Cornejo, J., & Frisvold, G. B. (2016). Economic returns to herbicide resistance management in the short and long run: The role of neighbor effects. *Weed Science*, *64*(S1), 595–608. https://doi.org/10.1614/WS-D-15-00047.1

McElroy, J. S., Flessner, M. L., Wang, Z., Dane, F., Walker, R. H., & Wehtje, G. R. (2013). A Trp_{574} to Leu amino acid substitution in the ALS gene of annual bluegrass (*Poa annua*) is associated with resistance to ALS-inhibiting herbicides. *Weed Science*, *61*(1), 21–25. https://doi.org/10.1614/WS-D-12-00068.1

Norsworthy, J. K., Ward, S. M., Shaw, D. R., Llewellyn, R. S., Nichols, R. L., Webster, T. M., Bradley, K. W., Frisvold, G., Powles, S. B., Burgos, N. R., Witt, W. W., & Barrett, M. (2012). Reducing the risks of herbicide resistance: Best management practices and recommendations. *Weed Science*, *60*(SP1), 31–62. https://doi.org/10.1614/WS-D-11-00155.1

Patton, A. J., Elmore, M., Kao-Kniffin, J., Branham, B., Christians, N., Thoms, A., Keeley, S., Nikolai, T., Watkins, E., Xiong, X., Gaussoin, R., Li, D., Gardner, D., Landschoot, P., Soldat, D., & Koch, P. (2022). *Turfgrass weed control for professionals* (Purdue University Extension Publication no. TURF-100). Purdue University.

Patton, A. J., Weisenberger, D. V., & Schortgen, G. P. (2018). 2, 4-D–resistant buckhorn plantain (*Plantago lanceolata*) in managed turf. *Weed Technology*, *32*(2), 182–189. https://doi.org/10.1017/wet.2017.98

Perry, D. H., McElroy, J. S., Dane, F., Van Santen, E., & Walker, R. H. (2012). Triazine-resistant annual bluegrass (*Poa annua*) populations with Ser_{264} mutation are resistant to amicarbazone. *Weed Science*, *60*(3), 355–359. https://doi.org/10.1614/WS-D-11-00200.1

Powles, S. B., & Yu, Q. (2010). Evolution in action: plants resistant to herbicides. *Annual Review of Plant Biology*, *61*, 317–347. https://doi.org/10.1146/annurev-arplant-042809-112119

Pritchard, B. D. (2022). *A bioassay to determine Poa annua responses to indaziflam* (Master's thesis, University of Tennessee). https://orcid.org/0000-0001-8592-0727

Retzinger, E. J., & Mallory-Smith, C. (1997). Classification of herbicides by site of action for weed resistance management strategies. *Weed Technology*, *11*(2), 384–393. https://doi.org/10.1017/S0890037X00043116

Rutland, C. A., Russell, E. C., Hall, N. D., Patel, J., & McElroy, J. S (2022). Resolving issues related to target-site resistance detection in *Poa annua* alpha-tubulin. *International Turfgrass Society Research Journal*, *14*(1), 808–811. https://doi.org/10.1002/its2.108

Schroeder, J., Barrett, M., Shaw, D. R., Asmus, A. B., Coble, H., Ervin, D., Jussaume, R. A., Owen, M. D. K., Burke, I., Creech, C. F., Culpepper, A. S., Curran, W. S., Dodds, D. M., Gaines, T. A., Gunsolus, J. L., Hanson, B. D., Jha, P., Klodd, A. E., Kniss, A. R., … Vangessel, M. J. (2018). Managing wicked herbicide-resistance: Lessons from the field. *Weed Technology*, *32*(4), 475–488. https://doi.org/10.1017/wet.2018.49

Shaner, D. L. (2014). *Herbicide handbook of the Weed Science Society of America*. Weed Science Society of America.

Shaw, D. R., Frisvold, G., Ervin, D. E., Sword, G. A., & Jussaume, R. A., Jr. (2020). *Stewardship challenges for new pest management technologies in agriculture*. Council for Agricultural Science and Technology (CAST).

Singh, V., Reis, F. C., Reynolds, C., Elmore, M., & Bagavathiannan, M. (2021). Cross and multiple herbicide resistance in annual bluegrass (Poa annua) populations from eastern Texas golf courses. *Pest Management Science*, *77*(4), 1903–1914. https://doi.org/10.1002/ps.6217

Svyantek, A. W., Aldahir, P., Chen, S., Flessner, M. L., Mccullough, P. E., Sidhu, S. S., & McElroy, J. S (2016). Target and nontarget resistance mechanisms induce annual bluegrass (*Poa annua*) resistance to atrazine, amicarbazone, and diuron. *Weed Technology*, *30*(3), 773–782. https://doi.org/10.1614/WT-D-15-00173.1

Van Wychen, L. (2020). 2020 Survey of the Most Common and Troublesome Weeds in Grass Crops, Pasture & Turf in the United States and Canada. Weed Science Society of America National Weed Survey Dataset. https://wssa.net/wp-content/uploads/2020-Weed-Survey_grass-crops.xlsx

Varco, J. J., & Sartain, J. B. (1986). Effects of Phosphorus, Sulfur, Calcium Hydroxide, and pH on Growth of Annual Bluegrass. *Soil Science Society of America Journal*, *50*, 128–132. https://doi.org/10.2136/sssaj1986.03615995005000010025x

Vila-Aiub, M. M., Neve, P., & Powles, S. B. (2009). Fitness costs associated with evolved herbicide resistance alleles in plants. *New Phytologist*, *184*(4), 751–767. https://doi.org/10.1111/j.1469-8137.2009.03055.x

Weed Science Society of America. (2021). *Herbicide site of action (SOA) classification list*. Weed Science Society of America. https://wssa.net/wssa/weed/herbicides/

Zimdahl, R. L. (2013). *Fundamentals of weed science* (4th ed.). London, UK. Academic Press.

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